AD-A012 368

FEASIBILITY STUDY OF CYCLIC PRESSURE TESTING THICK-WALLED CYLINDERS

Naval Ordnance Station
Louisville, Kentucky

January 1975

REPORT NO. MT-028
JANUARY 1975

FEASIBILITY STUDY OF CYCLIC PRESSURE TESTING THICK WALLED CYLINDERS

PHASE I

A MANUFACTURING TECHNOLOGY PROJECT
FOR THE
FACILITIES AND EQUIPMENT DIVISION, SEA-070
NAVAL SEA SYSTEMS COMMAND

FINAL REPORT

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

CLEARED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

1. ORIGINATING ACTIVITY (Corporate author) Naval Ordnance Station Louisville, Kentucky 40214	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Feasibility Study of Cyclic Pressure Testing Thick-walled Cylinders

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report of Phase I

5. AUTHOR(S) (First name, middle initial, last name)

6. REPORT DATE January 1975	7a. TOTAL NO. OF PAGES 62	7b. NO. OF REFS 1
8a. CONTRACT OR GRANT NO. b. PROJECT NO. WR 4-5896 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) MT-026 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

10. DISTRIBUTION STATEMENT

Cleared for public release - Distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Ordnance Systems Command Industrial Resources & Facilities Division (ORD-047), Washington, D.C. 20360

13. ABSTRACT

This study was initiated to investigate the feasibility of cyclic pressure testing thick-walled cylinders using electrohydraulic energy. The primary intended end use is an economical means of cyclic loading Naval Gun Barrels to safely determine their fatigue life. Preliminary examination was conducted on sample sections of a 5-inch gun barrel to verify design of end restraints, parabolic shaper, and reflector. Energy levels of 42 and 52 kilojoules (8,000 and 10,000 volts) were used, and pressures in the order of 40,000 to 68,000 psi were generated. From this data, further tests were conducted with an electrohydraulic equipment manufacturer to examine rapid cycling and pressure measuring equipment. The results obtained substantiate the use of the technique for cyclic pressure testing; however, it is considered that additional work is needed to design and produce more reliable components to optimize the process.

DD FORM 1473 (PAGE 1)

0102 014 6600

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fatigue testing						
Cylic testing						
Pressure testing						
Electrohydraulic						
Electrohydraulic pressure						
Thick-walled cylinders						

ia

REPORT NO. MT-026
JANUARY 1975

FEASIBILITY STUDY OF CYCLIC PRESSURE TESTING

THICK WALLED CYLINDERS

PHASE I

A MANUFACTURING TECHNOLOGY PROJECT
FOR THE
FACILITIES AND EQUIPMENT DIVISION, SEA-070
NAVAL SEA SYSTEMS COMMAND

FINAL REPORT

NAVAL ORDNANCE STATION
LOUISVILLE, KENTUCKY 40214

ib

CLEARED FOR PUBLIC RELEASE
DISTRIBUTION UNLIMITED

ABSTRACT

This study was initiated to investigate the feasibility of cyclic pressure testing thick-walled cylinders using electrohydraulic energy. The primary intended end use is an economical means of cyclic loading Naval Gun Barrels to safely determine their fatigue life. Preliminary examination was conducted on sample sections of a 5-inch gun barrel to verify design of end restraints, parabolic shaper, and reflector. Energy levels of 42 and 52 kilojoules (8,000 and 10,000 volts) were used, and pressures in the order of 40,000 to 68,000 psi were generated. From this data, further tests were conducted with an electrohydraulic equipment manufacturer to examine rapid cycling and pressure measuring equipment. The results obtained substantiate the use of the technique for cyclic pressure testing; however, it is considered that additional work is needed to design and produce more reliable components to optimize the process.

FOREWORD

This is the final report of work completed under NAVORDSYSCOM Work Request WR 4-5898 issued to perform a feasibility study of cyclic pressure testing thick-walled cylinders using electrohydraulic energy.

The study was performed by the Naval Ordnance Station, Louisville, Kentucky, with funds provided by the Industrial Resources and Facilities Division (ORD-047) of NAVORDSYSCOM under the Manufacturing Technology Program.

Preceding page blank

TABLE OF CONTENTS

Preceding page blank

SECTION I

INTRODUCTION

1.1 SCOPE

This study was performed to investigate the feasibility of cyclic pressurizing thick-wall cylinders using electrohydraulic energy. This information is to be used for fatigue life studies of gun barrel sections. In conjunction with this work, a program was conducted to develop parameters necessary to determine fatigue crack growth occurring during life tests.

1.2 BACKGROUND

Gun barrels, such as those used in the Fleet, are subjected to localized temperature changes on the inner bore surface during firing exercises. These cyclic thermal stresses produce incipient ruptures in the skin, which may develop into a well defined heat check network. Some of the heat checks, under cyclic loading, develop to crack conditions and, if allowed to continue, would cause the gun barrel to rupture.

It is most important to determine the useful life of gun barrels, that is, to remove them from service prior to failure but only after maximum service life is attained. It is this period of time and loading which is of interest to maintain gun barrel economy; and, for this purpose, the cyclic pressure testing of barrel sections was developed to safely determine their fatigue life.

The method presently employed at the Army Arsenal at Watervliet, and also for tests on Navy barrels, is the hydrostatic pressure cycling test. This test employs a close-fitting, high-strength steel mandrel to keep water volume at a minimum. High pressure pumps then cycle the water up to the desired test pressure, thirty to fifty thousand psi depending on barrel design, caliber, etc. It is apparent this type of testing duplicates the maximum pressure experienced in a barrel during firing; however, what is lacking is the rapid rise time to pressure comparable to that attained during the firing mode. It was opinioned this could be accomplished using a high energy metalworking process - electrohydraulics.

Electrohydraulics is a metalworking process which employs the instantaneous release of controlled quantities of stored electrical energy through a submerged spark plug or bridge wire. The electrical energy either ionizes a path in the spark gap or vaporizes the bridge wire, generating high velocity shock waves in the water. The spark gap method lends itself to the study as the bridge wire technique is unsuited to rapid sequence cycling.

During fatigue life cycling tests, some manner of monitoring crack growth is necessary. A method used by the Watervliet Arsenal utilizes ultrasonic inspection (reference (1)). A technique similar to that described was developed for electrohydraulic fatigue cycling. This method was refined to a point where crack depth approaching 0.050" was discernible. The report of the concern contracted to conduct this portion of the test is contained in Appendix I.

SECTION II

TECHNICAL APPROACH

2.1 PRELIMINARY TESTING

The initial portion of the study was conducted with an electrohydraulic machine at the Naval Air Rework Facility, Alameda, California. This machine produces up to 96,000 joules of energy with 18,500 volts.

Two sections of a Mk 18 Mod 1 gun barrel, 35" long, were prepared for the test. As a result of machining errors, one barrel section was scrapped. Preparations included facing the section ends for O-ring seal contact and machining three ports along the section length for pressure transducer location. The pressure transducers, Kistler Model 207C3 were designed to be used in pressure media up to 100,000 psi.

A shaper and reflector were designed to direct the pressure pulse in the barrel section. The parabolic shaper focused the pulse into a long, narrow shock wave which was directed by the reflector to the surface of the bore. The conical form of the reflector also served to keep the pulse intensity constant as it travelled along the section length.

The test assembly (Figure 1) consisting of end restraints, reflector, barrel and shaper was designed to fit the maximum press opening. The electrohydraulic transducer (spark gap) in the lower press platen also contained the waterfill outlet.

Energy levels of approximately 42 and 52 kilojoules (8,000 and 10,000 volts respectively) were discharged for test observations. The data obtained during this portion of the test is discussed in paragraph 3.1.

2.2 EVALUATION

The problems encountered during this initial testing prompted the following recommendations prior to continuing the investigation:

a. Electrohydraulic equipment more suited to the rapid cycling necessary for fatigue life studies was to be used. A minimum cycle time of 4 shots per minute was the goal.

b. More uniform energy pulse. This was a design problem which has been incorporated into later model equipment.

c. It was desired to obtain more supporting data during later tests. Data to this time was recorded with a dual trace oscilloscope; a magnetic tape recorder proved incapable of operation in the high electric field in the area of the electrohydraulic machine.

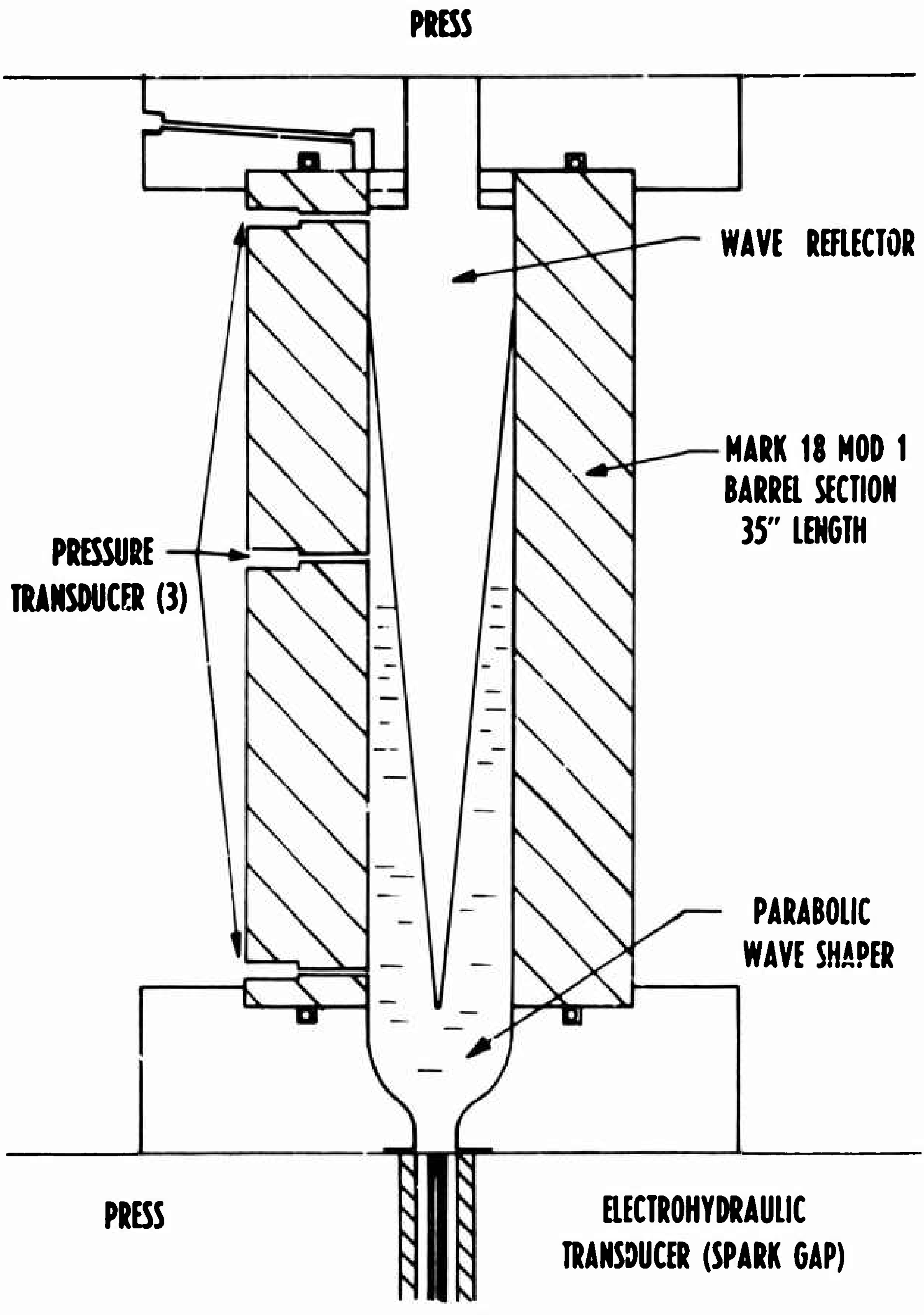


FIGURE 1 TEST ASSEMBLY

d. Further tests were to be continued with electrohydraulic equipment at the Soniform, Incorporated firm of La Mesa, California. This firm manufactures electrohydraulic metalworking machines and was known to have personnel experienced in electrohydraulic metalforming. Parts for many jet engines are manufactured by this firm using the electrohydraulic process.

During the preliminary testing, it was anticipated pressures of 40,000 - 50,000 psi could be obtained. Tests conducted at the Naval Air Rework Facility indicated these pressures would be no problem. Energy levels used to reach these pressures were:

42 kilojoules - 8,000 volts
52 kilojoules - 10,000 volts

These preliminary tests were observed by personnel from the Soniform firm and it was opinioned, though their equipment had a maximum energy level of 40 kilojoules, that their equipment could yield the necessary pressures.

2.3 CYCLIC TESTING

A restraining fixture was designed and fabricated by Soniform which could hold the test assembly as used in the first trials, Figure 2. The gases generated during the spark discharge required bleeding after each shot so a gas bleed in the upper portion of the assembly controlled the firing switch. While the gases were bled from the section, the capacitor bank would charge but the firing circuit was interrupted. As the gaseous mixture cleared the section, a continuous stream of water would be emitted through the hose, actuating the switch to complete the firing circuit. In this manner, cycle times of four per minute were obtained. The longest, continuous number of cycles obtained in this manner was over 600 cycles. The total number of pressure cycles obtained exceeded 4,500.

During this portion of the testing, a method of determining crack initiation and propagation was developed. The report concerning this portion of the program is contained in Appendix I.

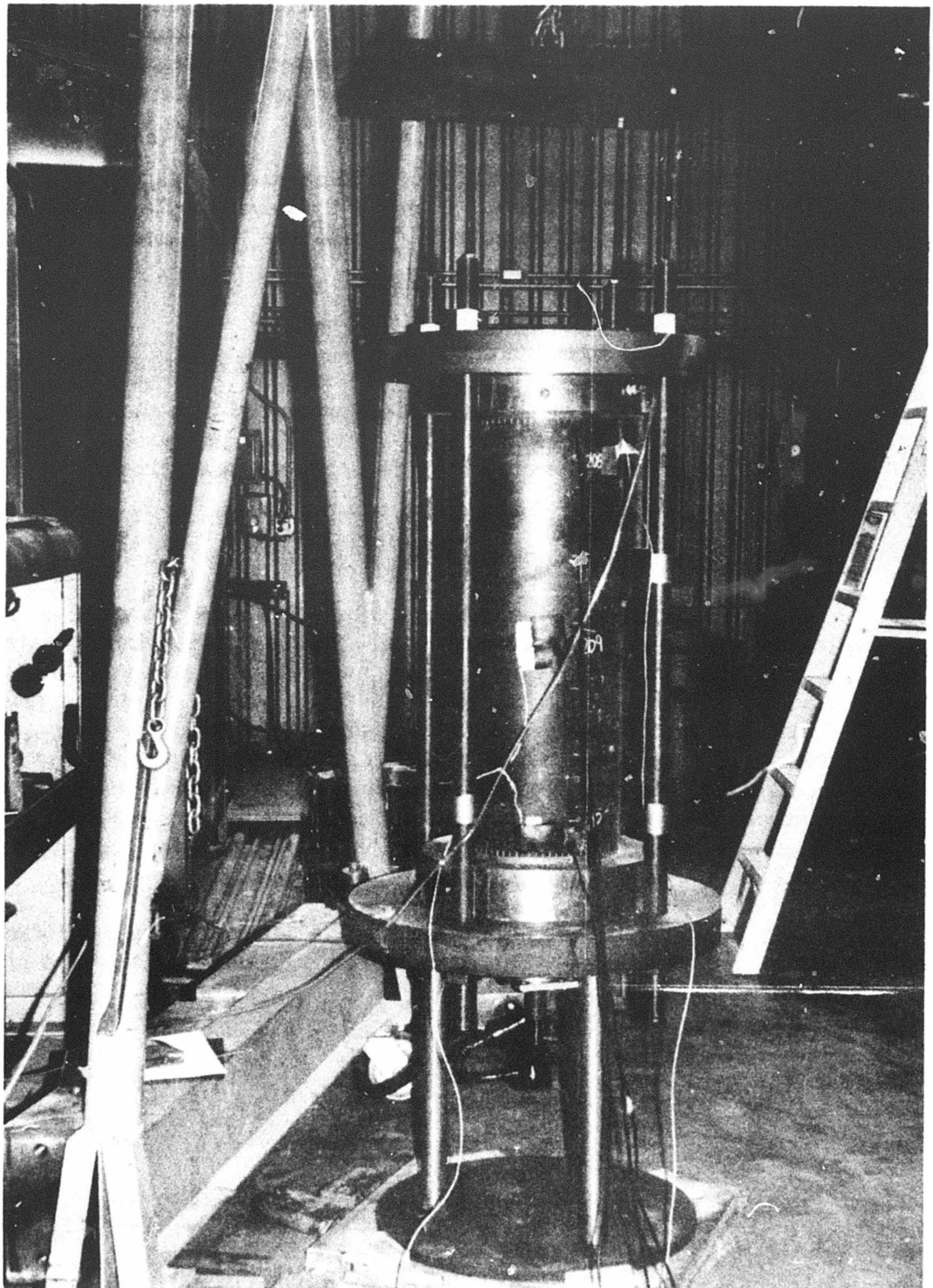


FIGURE 2 ELECTROHYDRAULIC TEST ASSEMBLY

SECTION III

TEST RESULTS

3.1 PRELIMINARY INVESTIGATION

3.1.1 Instrumentation

Kistler transducers Model 207C3 used in ballistic data gathering for pressures up to 100,000 psi were placed in the barrel section. Three transducers were located along the barrel section length at equal intervals; in this manner, the pressure pulse at the origin of the shock wave could be obtained and compared with pressures at the center and end of the section.

A cathode-ray oscilloscope with the capability to register and store a dual trace was used to determine transducer output. A camera attachment filmed the trace, etc. A Honeywell 5600 Instrumentation Tape Recorder was also used to record the transducer output signal. A Kistler 504D Dualmode Amplifier received the transducer signal and amplified it for the tape recorder. The recorder has multichannel capabilities which were used to monitor the signal to the oscilloscope. The proximity of this instrument to the electromagnetic-metalworking equipment resulted in the recording of spurious information. The electric-field generated during triggering the spark transducer nullified any data gathered on this equipment.

3.1.2 Results

The conditions of the electrohydraulic equipment precluded cycling of the capacitor bank for rapid cycle fatigue testing. During the major portion of the time allotted for the test, the machine was incapable of cycling rapidly. A timer, finally located after the scheduled test time as nearly completed, was the culprit for the low number of cycles conducted during this phase of the test. Of the 50 cycles obtained the instrumentation problems discussed in paragraph above occurred. Therefore, the output readings of only approximately 30 cycles was obtained. These data and discussion follow:

<u>18,500 volts - 96 kilojoules</u>

<u>Pressure Transducer Locations:</u>

Position 1. - Bottom of barrel section

Position 2. - Center of barrel section

Position 3. - Top of barrel section

18,500 volts - 96 kilojoules

Pressure Transducer Locations:

Position 1. - Bottom of barrel section

Position 2. - Center of barrel section

Position 3. - Top of barrel section

8,000 volts - 42 kilojoules

	Tape Recorder Location	Oscilloscope Camera
Position 1.	34,000 psi	40,000 psi
Position 2.	50,000 psi	50,000 psi
Position 3.	34,000 psi	48,000 psi

Murphy's Law #3 - If there is a possibility of several things going wrong, the one that will go wrong will result in the most damage.

10,000 volts - 52 kilojoules

	Tape Recorder Location	Oscilloscope Camera
Position 1.	45,000 psi	53,000 psi
Position 2.	[illegible] 000 psi	68,000 psi
Position 3.	3[illegible]00 psi	62,000 psi

The pressure readings recorded on the tape recorder were unsubstantiated and have been deleted. The recorder, when recording independently with no hookup to the oscilloscope, would trigger haphazardly. When used in conjunction with the oscilloscope, data would agree with the particular pressure transducer being monitored, but the other two readings would be inconclusive. It was opinioned that the recorder was too close to the capacitor bank and effects from the electric field were interfering with the proper operation of the recorder.

3.1.3 Findings

This portion of the test was terminated and preparations for additional tests were made. Based on the results of the early tests, it was apparent that the pressures sought could be reached but other factors now had to be resolved, among these were:

(1) More consistent energy discharge across the spark transducer gap.

(2) Electrohydraulic metalworking equipment which could be cycled rapidly. A cycle time of 4 shots per minute was the goal.

(3) Instrumentation would be placed in a more remote location from the test site to isolate it from electric field effects; also a method other than the pressure transducers would be used to substantiate the pressure transducer readouts.

(4) A method to determine the location of crack initiation as well as crack propagation was to be developed. The process presently used by the Army in their gun barrel fatigue testing was used as a starting point. (Reference (1)).

3.2 PROGRAM CONTINUATION

The services of an industrial firm which manufactures electrohydraulic equipment were contracted for the balance of this study. At the time of the preliminary testing, a representative of a firm, Soniform, Incorporated was present and some of the problems were discussed. It was opinioned that the barrel pressures attained with that equipment could be reproduced with the Soniform equipment, though the Soniform equipment was rated at a lower capacity. This opinion was based upon instances where Soniform had rebuilt similar equipment and reduced the power levels from that previously used to form the same part.

3.2.1 Instrumentation

The same pressures transducers used in the preliminary study were employed. An oscilloscope with capabilities similar to the first was also used.

Personnel overseeing instrumentation recommended strain gages to correlate the data of the pressure transducers. It was anticipated the oscilloscope and tape recorder would than alternately monitor the information from these two devices. Both the recorder and oscilloscope were placed where no effects from electric fields were anticipated.

It was apparent from the onset of this test that the only instrumentation which could be used would be the pressure transducers and the oscilloscope. The instrumentation had been thoroughly checked out and inspected prior to the test and still it was of little use in this type of testing. The strain gages, though adequately protected against stray electrical current, arced repeatedly during the test. The sensitivity of the recorder to the intense electrical energy generated resulted in the instrument triggering and recording while completely isolated from the test assembly.

During rapid cycling, the pressure transducers were monitored alternately with the camera attachment and these results follow:

Test Cycle	Pressure (psi)	Transducer Location
2	27,500	Top
2	40,000	Bottom
3	15,000	-
4	20,000	Bottom
5	27,500	Bottom
6	35,000	Top
7	20,000	Bottom (17 KV)
8	12,500	Top (17 KV)
9	12,500	Top (17 KV)
10	12,500	-
-	20,000	Bottom
-	20,000	Bottom
90	20,000	Bottom
100	28,750	Top
245	25,000	Top
248	25,000	Top
242	28,000	Top
244	25,000	Top
-	30,000	Top

Transducers failed

Explanation - The transducers were returned to Kistler for evaluation and recommendations for more suitable transducers. Failures were attributed to extremely high mechanical shock as reported by Sundstrand Data Control, Incorporated.

SECTION IV

CONCLUSIONS

4.0 Though the pressures were low, the test was continued to determine other factor related to the testing as well as to point out possible problem areas. The Ultrasonic inspection technique was developed and this report is attached (Appendix I).

By combining the results of the preliminary and subsequent tests, the following results are concluded. The pressures required to stress the barrel can be reached with adequate energy; cycle times of four per minute for long periods of time are possible and the ultrasonic inspection technique was proven suited to the process.

Problems disclosed by the rapid cycle times and high energy levels were expediently corrected where possible. Other problems will be resolved in a short development study to be conducted when further work is authorized.

Problems such as cabinet heat, firing switch heat, cable connection, test assembly fixturing, and low energy can all be solved by designing equipment to suit the purpose.

The spark transducer problem can be solved in a short development study to develop a long life economical transducer. This will require comparing life versus material costs. Cooling of the spark transducer will extend the life markedly and this also can be designed into the equipment.

It will also be necessary to conduct short run design tests on reflector shapes and transducer designs to "fine tune" the process. This will be run concurrent with the transducer tests

SECTION V

RECOMMENDATIONS

5.0 Since the initiation of this preliminary study, much interest has been directed toward the electrohydraulic process to create high pressure shock waves to stress various gear. The West German Defense Ministry and NWL/Dahlgren as well as the Army Arsenal (Watervliet) have requested that they be kept aware of the development. The first two facilities have sent representatives to Naval Ordnance Station, Louisville seeking additional information.

From the results of this study, it is recommended further funding be authorised as requested in the original proposal.

Preceding page blank

APPENDIX I

ULTRASONIC TESTING

Preceding page blank

DEVELOPMENT AND APPLICATION OF FOCUSED CONTACT ULTRASONIC TECHNIQUE FOR 5-INCH NAVY GUN BARRELS

By

John R. Zurbrick, P.E.

Consultant

Nondestructive Evaluation

Preceding page blank

CONTENTS

Preceding page blank

ABSTRACT

DEVELOPMENT AND APPLICATION OF FOCUSED CONTACT ULTRASONIC TECHNIQUE FOR 5-INCH NAVY GUN BARRELS

A hand-scanning, contact ultrasonic technique was developed to provide a nondestructive means for detecting and measuring fatigue crack growth in 5-inch high-strength steel Navy gun barrels. Refinements included a double-refracting, concavo-concave focusing lens to concentrate the ultrasound energy where it was most needed. Included was the application of the developed technique to monitoring fatigue crack growth associated with electrohydraulic impulse loading of one three-foot breach-end length of a 5-inch gun barrel section. Calibration and test procedures, and results of the inspections are reported.

Preceding page blank

LIST OF FIGURES

Preceding page blank

LIST OF TABLES

Preceding page blank

INTRODUCTION

A. PURPOSE OF TASK

The specific purpose of this task was to provide a nondestructive means for detecting and measuring fatigue crack growth in 5-inch high-strength steel Navy gun barrels. Included was the application of the developed technique to monitoring fatigue crack growth associated with electrohydraulic impulse loading of one three-foot, breach-end length of 5-inch gun barrel section.

B. SCOPE OF THIS REPORT

The background and technical discussion briefly reviews the Navy's general need for fatigue crack measurement in fired gun barrels. It includes a critique of ultrasonic technique developments conducted by the U.S. Army toward measuring fatigue crack growth in artillary cannon tubes, and approaches to improve on that experience.

The technique development section details the technical basis for ultrasonic detection of fatigue cracks "end-on", which was the hypothesis used to create a technique which concentrated the interrogating energy where it was most needed. Design of transducer shoes with acoustical lenses, their assembly and use, and evaluation with a specially-designed calibration standard are covered in detail.

An ultrasonic test procedure was created to support the specific needs of the electrohydraulic impulse loading program. Instrument set-up, calibration, and measurement instructions are given in step-by-step fashion.

Four gun barrel scans were performed; one prior to electrohydraulic "firing", two in San Diego during the course of electrohydraulic impulse loading tests, and one after the gun barrel section was returned to NOSL Manufacturing Technology. The test data obtained are included in chart form.

Conclusions and recommendations are offered based on the experience of this task.

Preceding page blank

BACKGROUND

A. U.S. NAVY GUN BARREL FATIGUE CRACK PROBLEM

Navy gun barrels are life-limited by the fatigue crack growth process. Cost and logistics of shipboard gun barrel replacement and value of retired gun barrels in storage (many millions of dollars) provided the incentive to explore means to refine the prediction of cyclic life limits and develop means to nondestructively measure fatigue crack size in existing fired gun barrels (aboard ship and in storage).

B. ELECTROHYDRAULIC IMPULSE LOADING FOR PROPAGATION OF REPRESENTATIVE FATIGUE CRACKS

Naval Ordnance Station-Louisville (NOSL) has established a program to develop dynamic electrohydraulic pressurization as a means to conveniently and economically propagate gun barrel fatigue cracks which are representative of those produced during gun barrel firing, that is, stressed by an axially-traveling pressure wave. In the specific program related to the subject task, a three-foot long breach-end gun barrel section was fitted with an internal spark gap ("transducer"), pressure wave guide or horn (Electrohydraulic Test Fixture TD-14351) and filled with water. A capacitor bank was charged to 18 kilovolts and 40 kilojoules of energy, then discharged across the spark gap to produce a sharp pressure pulse. Three piezoelectric pressure transducers were used to measure pressure wave maximum, pulse duration and overall rate of wave travel along the gun barrel section. The dynamic pressure impulse loading tests were performed at Sonoform, Inc., San Diego, California, using a cycling rate of four firings per minute when operating. Success in the nondestructive test was to be demonstrated on the cracks to be grown at Sonoform, with the crack growth results serving to measure the success in using electrohydraulic pressurization to propagate firing-related gun barrel fatigue cracks.

C. NONDESTRUCTIVE EVALUATION OF GUN BARRELS

The U.S. Army developed a hand-scan contact ultrasonic technique for detecting the sound energy reflected from a fatigue crack tip (Reference 1). The "normal probe" technique was shown to reliably detect cracks 0.600 inch to 2.00 inches deep as measured from the bore. The cracks were produced in cyclic hydraulic loading tests. The normal probe was typically a 5 MHz contact ultrasonic transducer, 3/8 inch to ½ inch diameter, applied directly to the OD of the gun barrel, with water or oil couplant. Laboratory or full-size ultrasonic instrumentation was found to be most successful. A mechanical guide for hand scanning aided in efficient data-taking.

The subject task was prior-oriented toward application of the "normal probe" technique to the Navy gun barrel test program. The desire was to at least duplicate the Army experience, preferably improving acoustic detalis to obtain a highly-sensitive hand-scanning contact ultrasonic technique. The technique development effort was conducted wholly in reference to the background presented above.

TECHNIQUE DEVELOPMENT

A. TECHNICAL BASIS

The "normal probe" technique used a short pulse of 5 MHz longitudinal mode ultrasound traveling from gun barrel OD along a section radius line to the rifled bore. (Figure 1) Should a fatigue crack exist within the volume of steel being interrogated by the pulse beam path, it would most likely be oriented radially outward from the bore in depth, and lengthwise along the rifling helix. Therefore, the crack tip must interact with the ultrasound pulse in some manner to produce a return echo sufficiently large to be detected by the contact transducer, amplified, and displayed on the instrument oscilloscope. Such fatigue crack echos would always arrive before the large echo from the bore surface itself. By using the time-axis (horizontal) of the oscilloscope as a measure of distance in the steel (constant longitudinal velocity assumed), the radial outward depth of the crack could be determined from the graticule scale on the instrument. The Army was able to resolve .100 inch of depth at each minor division.

While a crack oriented parallel to the ultrasound beam path is in the worst possible position for crack echo reflection, the Army demonstrated that sufficiently large echos were obtained from the crack tip. Miller ascribed the cause to interactions with the roughness of the crack surfaces. This would indeed explain the gradual decline of the echos from the crack tip peak amplitude toward the bore echo. Fracture mechanics deals with crack growth and the plastic zone just ahead of, and into which grows, a fatigue crack (Figure 2). Ultrasound will reflect from this plastic zone and that hypothesis was used to guide the subject technique development effort.

The problem of obtaining echo signals from the crack tip plastic zone was studied specifically for the 5-inch gun barrel (Figure 3). Refraction of the OD of the gun barrel (12.75 inches) with a bare ½" contact transducer would seem at first to be negligible, however, calculations via Snell's Law:

$$\sin\beta = (V_S/V_W) \quad \sin\alpha$$

WHERE:
- α = incident angle in water, 2.2°
- β = refracted angle in steel, 8.9°
- V_S = longitudinal velocity in steel, .230 in./μsec.
- V_W = longitudinal velocity in water, .0587 in./μsec.

showed that the beam diverged by an included angle of 13.2 degrees. Beam cross-section at the bore was 1.40 inch circumferentially by ½ inch axially. Considering that only the energy incident on the plastic zone could be reflected, it was obvious that more than 90% of the energy in each pulse could not interact with a given crack.

FIGURE 1

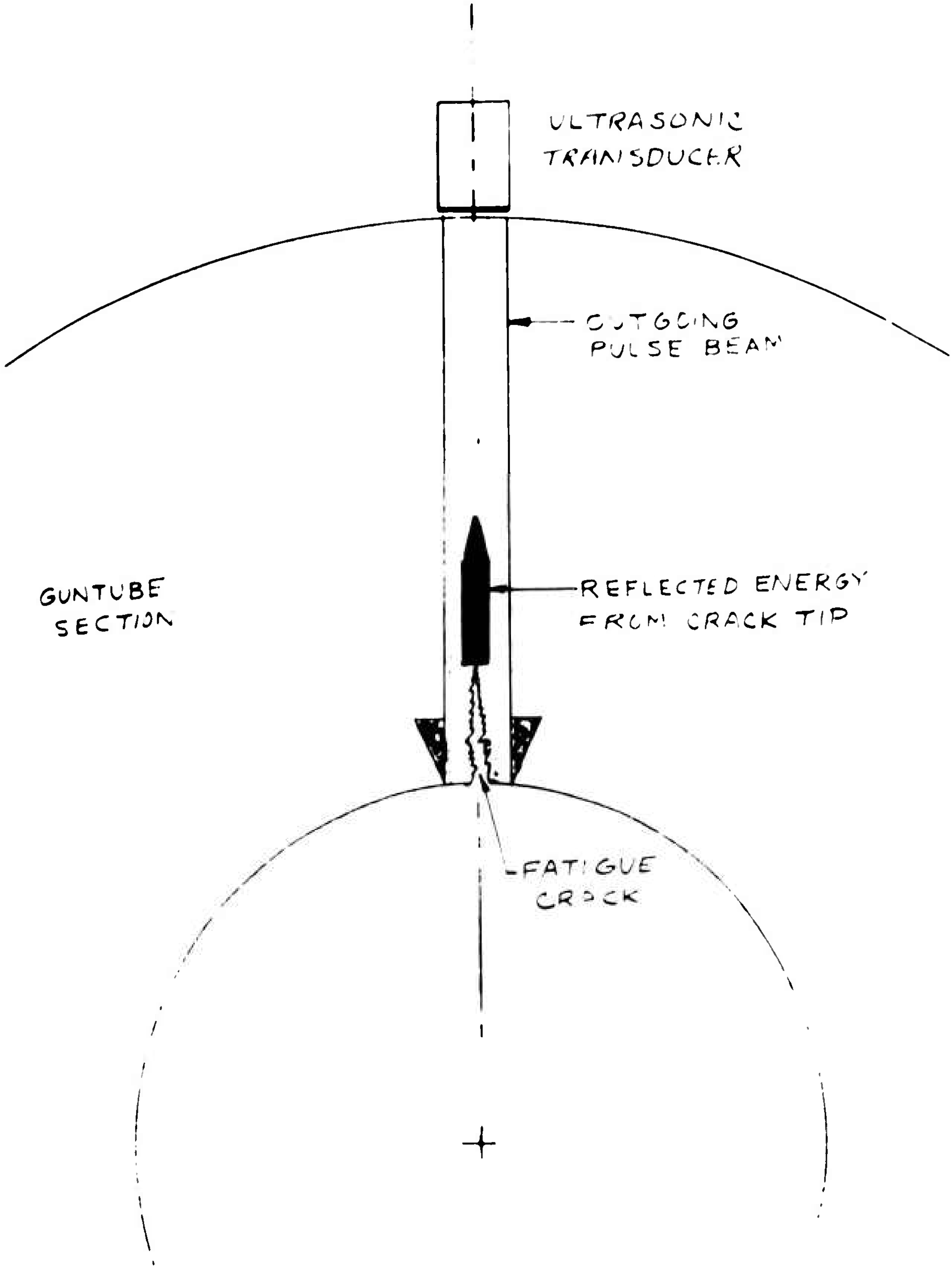

ULTRASONIC
TRANSDUCER
OUTGOING
PULSE BEAM
GUNTUBE
SECTION
REFLECTED ENERGY
FROM CRACK TIP
FATIGUE
CRACK

FIGURE 2

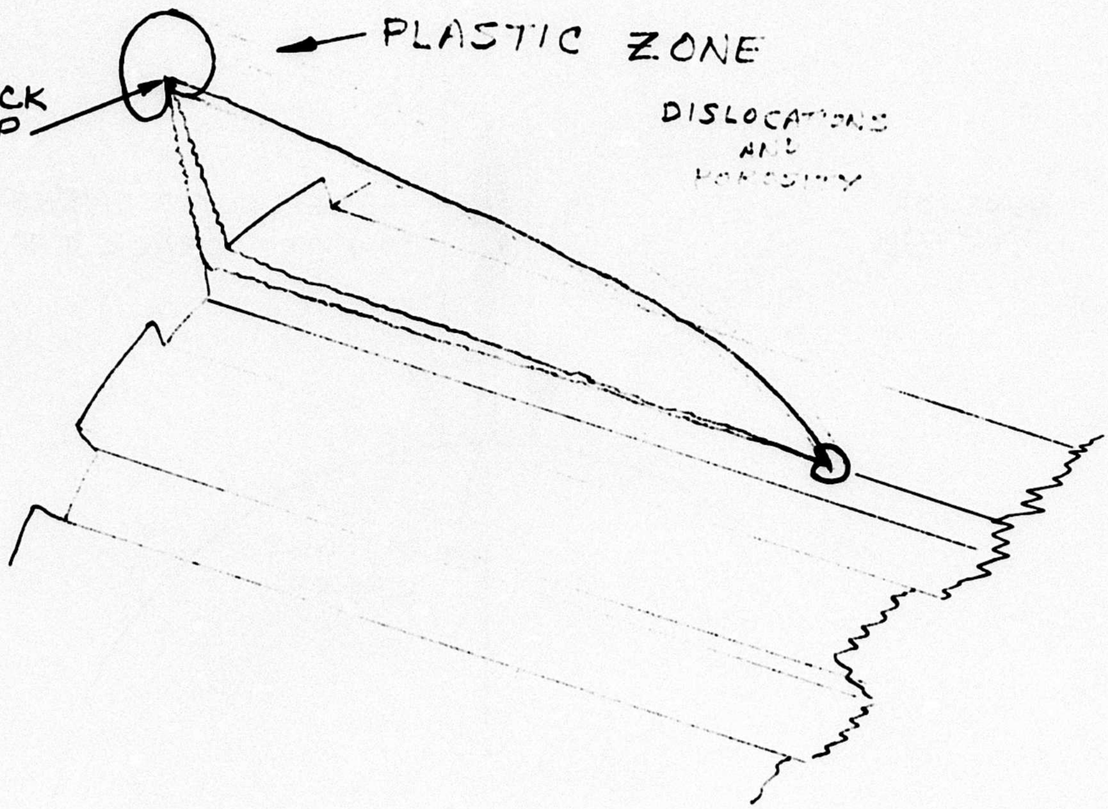
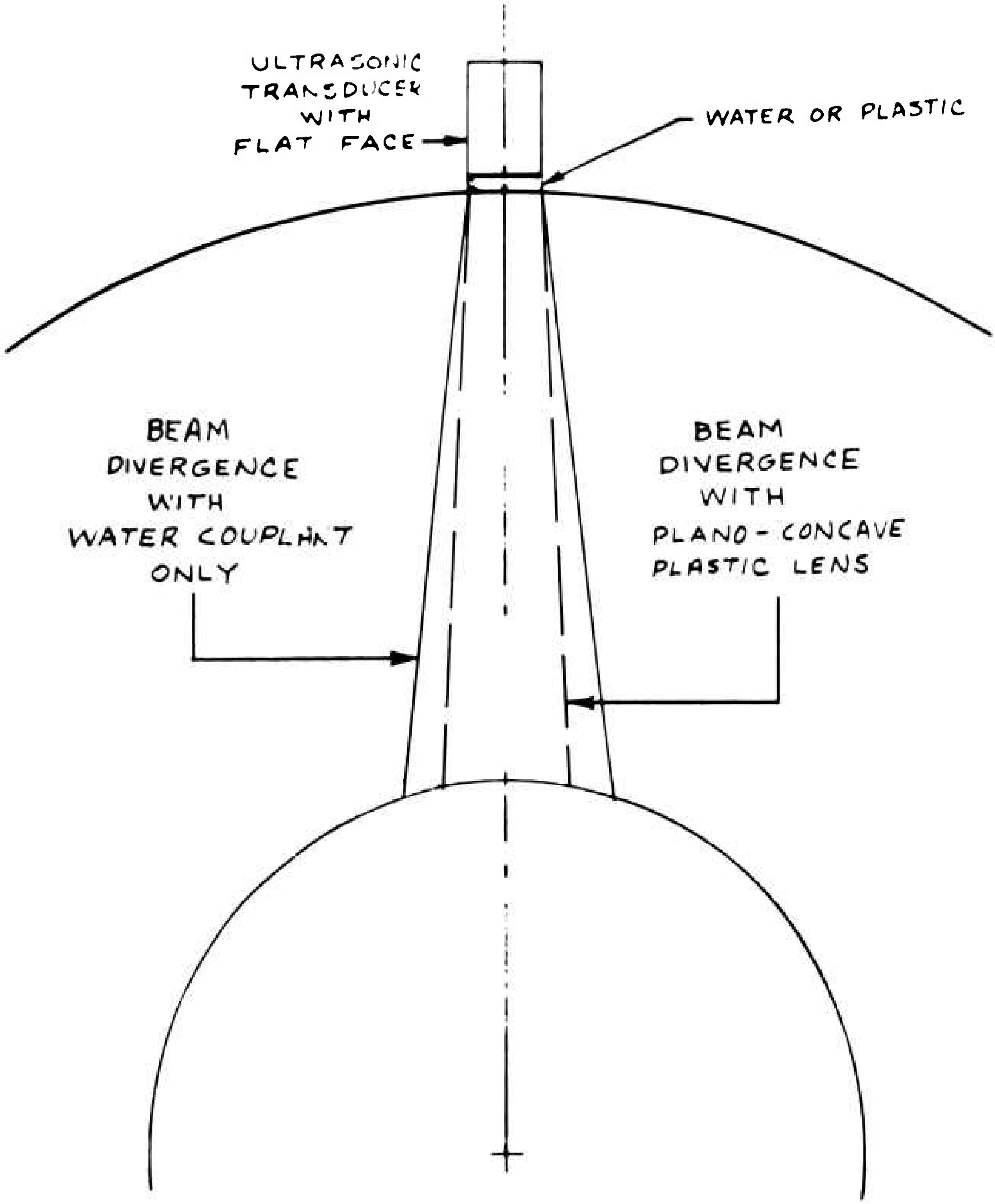


FIGURE 3


ULTRASONIC TRANSDUCER WITH FLAT FACE
WATER OR PLASTIC
BEAM DIVERGENCE WITH WATER COUPLANT ONLY
BEAM DIVERGENCE WITH PLANO-CONCAVE PLASTIC LENS

In addition, signal attenuation in the steel with travel along the ultrasound beam path (8 inches from OD-to-bore-to-OD) increased rapidly with the distance from OD surface to crack tip, further decreasing the ability to detect the shallow fatigue cracks.

A thin plastic (polymethylmethacrylate, i.e. Plexiglas or Lucite) shoe placed between the face of the ultrasonic contact transducer and the gun barrel OD surface so that all surfaces mated (plano-concave cylindrical lens) and coupled with a thin film of water or oil, resulted in a diminished divergent included angle of 5.4 degrees (V_p = longitudinal velocity of plastic, .105 in./μsec.) giving a beam section at the bore of .87 inches circumferentially by ½ inch axially.

Since no real advantage was obtained using a simple contour matching shoe, convergent focusing lenses were investigated.

The specific concept is shown in Figure 4. Desired minimum detection level was a crack 0.100 inch deep from the bore. The Army's experience gave a 90% probability of detection at 95% confidence limits for a crack 0.600 inch deep. Critical crack length was 2.50 inches deep from the bore.

Geometrical considerations for maximum energy concentration over the crack growth region of greatest interest placed the ultrasound beam focus at 0.400 inches from the bore, approximately 10% of the distance along the bore-to-OD radius line. Attenuation effects would also be well offset by the increasing beam intensity with distance from the OD.

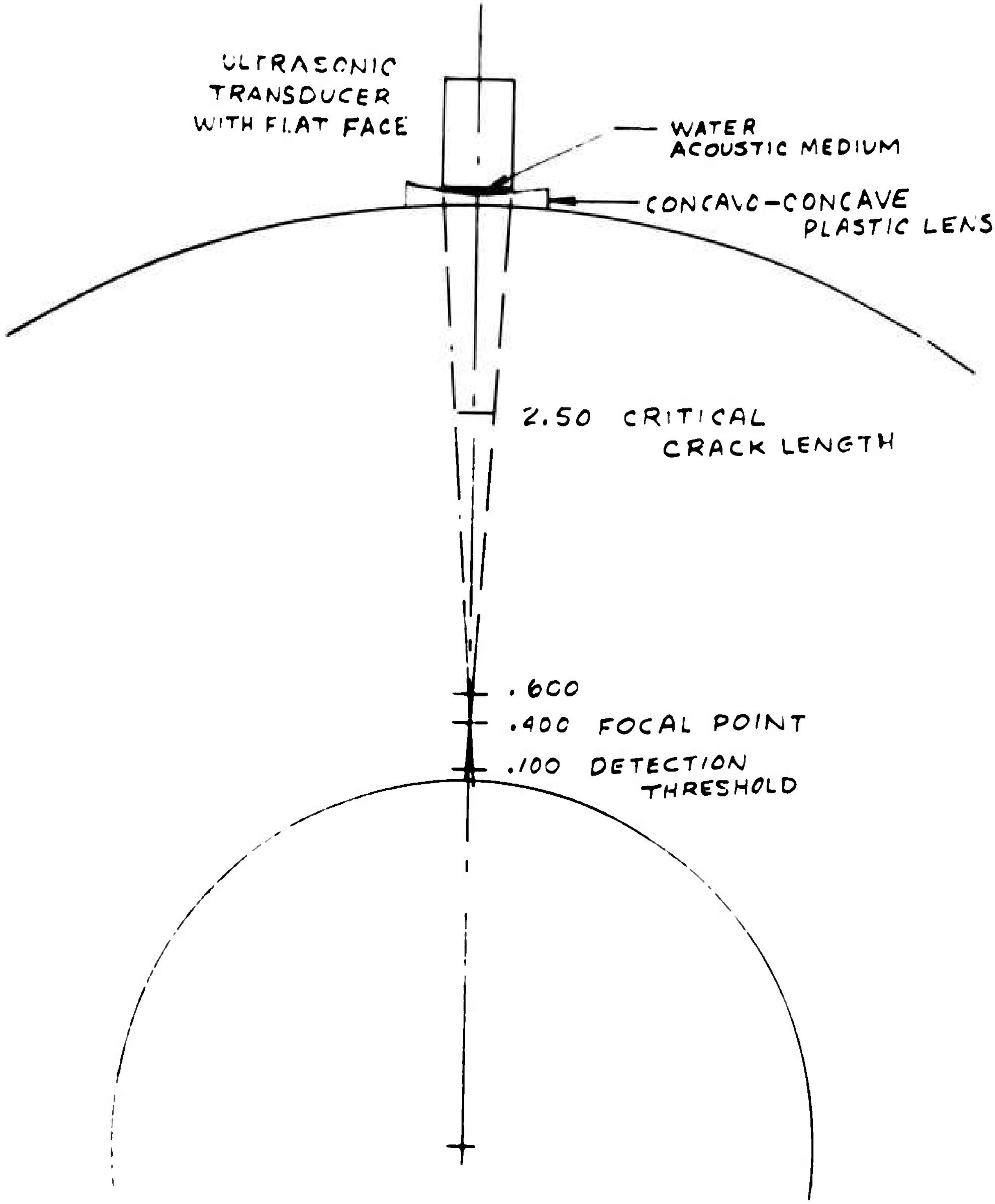
Reduction of idealized acoustical optics to a practical ultrasonic hand-scan contact technique required careful design of the transducer holder and focusing lens, careful attention to instrument set-up, and quantitative measurement of distances, times, and amplitudes associated with the oscilloscope display. The operator was included in the design by providing a minimum of opportunity for optical misalignment, a comfortable-to-hold unit, and a means to signal a defect indication at the transducer holder itself. A simple means for supplying a couplant (water) film between lens and gun barrel was retained in view of the limited testing to be performed within the scope of the subject task.

B. TRANSDUCER SHOE AND LENS DESIGN

The lens design was fixed by geometrical considerations associated with the selected focal point in the gun barrel;

- -radius of curvature of the gun barrel, inches (6.375)
- -focal position measured from OD, inches, (3.50)
- -diameter of the active element in the transducer, inch (.50)

FIGURE 4



ULTRASONIC TRANSDUCER WITH FLAT FACE
WATER ACOUSTIC MEDIUM
CONCAVO-CONCAVE PLASTIC LENS
2.50 CRITICAL CRACK LENGTH
.600
.400 FOCAL POINT
.100 DETECTION THRESHOLD

Snells' Law was used to calculate the radius of curvature of the necessary concavo-concave cylindrically-focusing lens, Figure 5. The beam pattern was wedge-shaped and aligned with the gun barrel axis/radial plane.

The general calculation approach used was to determine the incident and refracted angle relationships between water and acrylic plastic, and between plastic and gun barrel steel (both by Snells' Law) so that the direction and angle of the normal line for water/plastic could be found. Intersection with the radius line located the center of curvature and thereby radius of curvature. The lens was produced with a fly-cutter. Because small changes in curvature, either gun barrel OD or water/plastic radius of curvature, dramatically affect position of the focal point in the steel, the lens designed was specific to the subject task. Taper in the gun barrel or other bore-size gun barrels would require specific lens designs. A brief check on the use of such lens at the 7.0 inch OD muzzle-end indicated that the existing lens would be unsuitable and that a series of lenses would be necessary.

Details of the calculation procedure are proprietary to J.R. Zurbrick and beyond the scope of the subject task.

Use of a bare transducer, or a simple plano-concave shoe would be even more unsatisfactory at the muzzle-end than at the breach-end, due to the greater ultrasound beam divergence.

Water was used as a couplant and acoustic medium between transducer face and lens as a matter of convenience in supply and clean-up. Light motor oil could be directly substituted for couplant and acoustic medium with little effect on focus or performance. When oil is to be definitely used, however, the lens design should be based on its acoustic velocity, rather than that of water.

The transducer holder design, Figure 6, provided a hydraulically-tight fit between the Automation Industries Style 57A 2217 transducer (SFZ-5.0 MHz-.5 inch dia.) and the main bore-hole, using a Parker -016 O-ring seal. This trapped the water acoustic medium and held the transducer firmly in place. The slot provided entry for the transducer cable and microdot connector and the alarm light cable. The cap plate protected the alarm light and assured transducer positioning. Overall size and offset of the main bore-hole was designed to give best access near end flanges of the test rig, suitable assurance of optical alignment and operator hand comfort.

Primary assembly of the lens to the transducer holder was with two-part, room-temperature curing clear epoxy, assuring proper alignment and water-tight seal. The transducer was fitted with the O-ring (this style transducer includes the proper O-ring groove), then the O-ring and bore-hole were lightly greased with petroleum jelly.

FIGURE 5

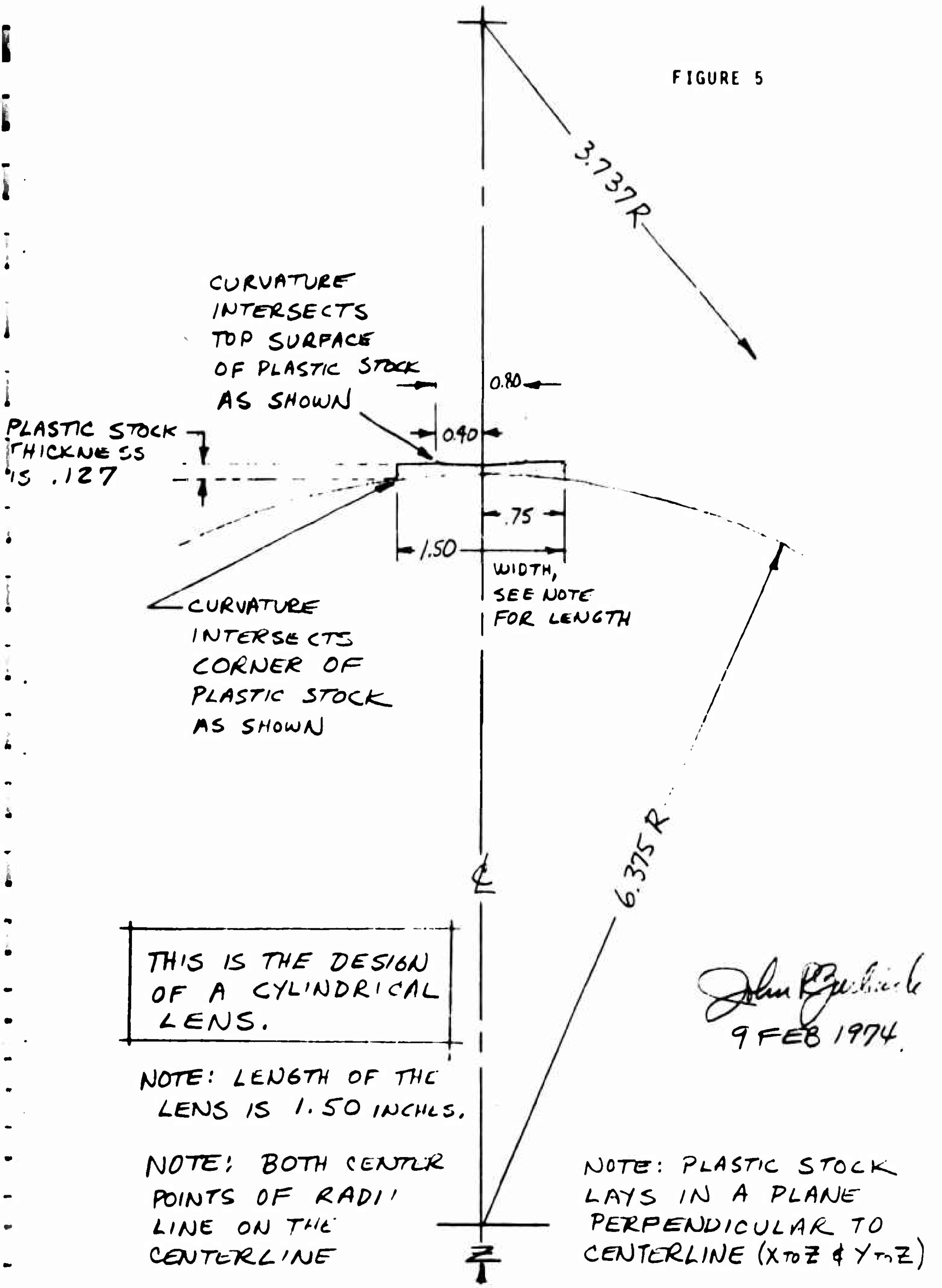
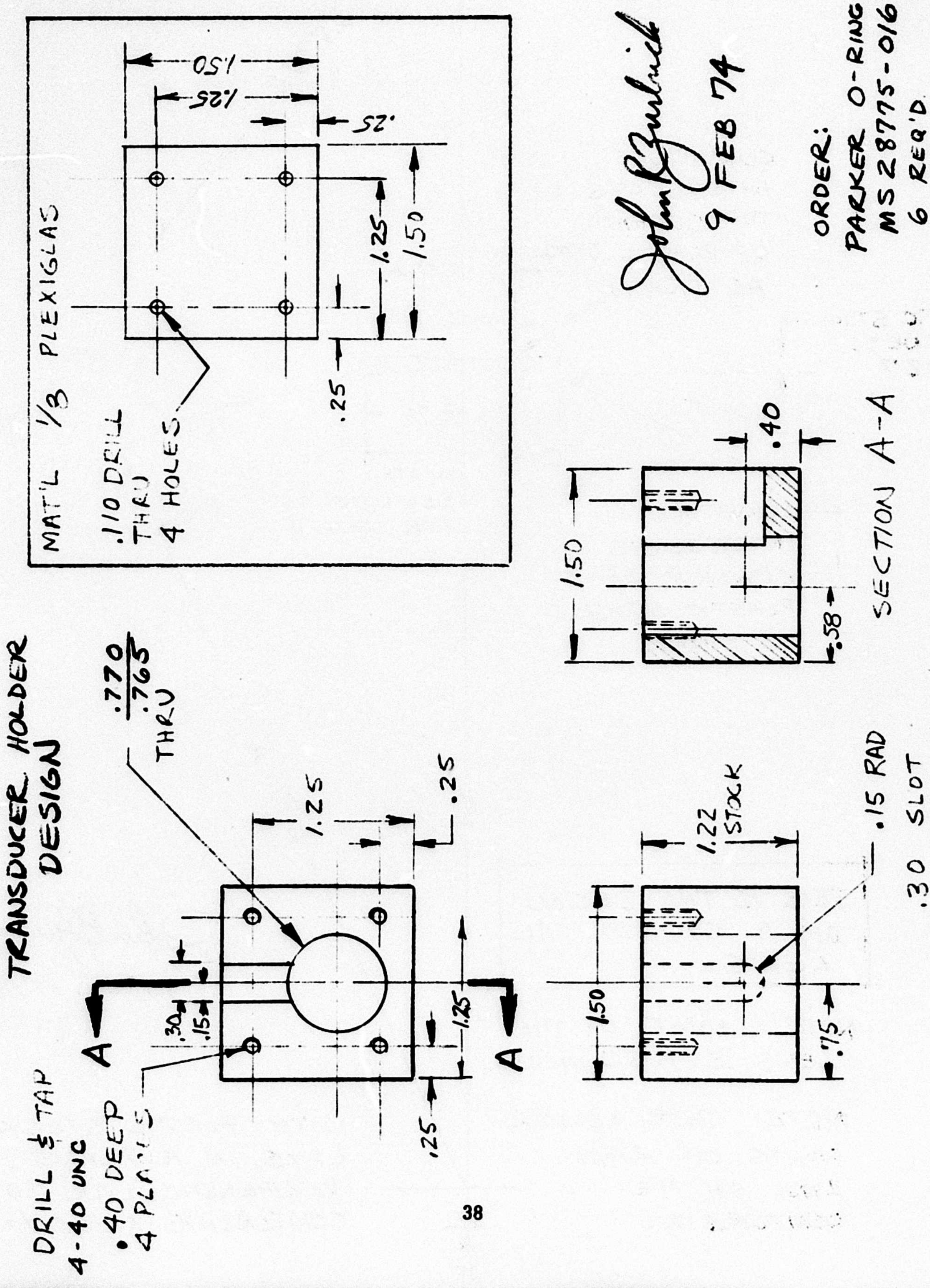

3.737R
CURVATURE INTERSECTS TOP SURFACE OF PLASTIC STOCK AS SHOWN
0.80
0.40
PLASTIC STOCK THICKNESS IS .127
.75
1.50
WIDTH, SEE NOTE FOR LENGTH
CURVATURE INTERSECTS CORNER OF PLASTIC STOCK AS SHOWN
6.375R
℄
Z
THIS IS THE DESIGN OF A CYLINDRICAL LENS.
NOTE: LENGTH OF THE LENS IS 1.50 INCHES.
NOTE: BOTH CENTER POINTS OF RADII LINE ON THE CENTERLINE
NOTE: PLASTIC STOCK LAYS IN A PLANE PERPENDICULAR TO CENTERLINE (X TO Z & Y TO Z)
9 FEB 1974

FIGURE 6



TRANSDUCER HOLDER DESIGN
MAT'L 1/8 PLEXIGLAS
.110 DRILL THRU 4 HOLES
.770
.765
THRU
DRILL & TAP 4-40 UNC .40 DEEP 4 PLACES
1.22 STOCK
.15 RAD
.30 SLOT AS SHOWN
SECTION A-A
9 FEB 74
ORDER:
PARKER O-RING
MS28775-016
6 REQ'D

Insertion of the transducer was accomplished with a suitably long, thin sewing needle. This procedure allowed the excess water to escape until the transducer had seated against the lens. Quick removal of the needle established the desired hydraulic seal (care was taken to exclude all air bubbles). This arrangement assured reproducible optical alignment. (For a transducer not amenable to the O-ring seal concept, a plastic set-screw would position the transducer. Other seal and bleed hole arrangements would be needed to contain the acoustic medium).

Once the transducer was in place the alarm light (light-emitting diode, LED) was set in rubber washers, placed on the top of the transducer and the cap screwed down.

The full transducer-holder assembly is pictured in Figure 7. Two complete units were fabricated and delivered.

The wiring diagram between ultrasonic instrument (Automation Industries UM771/10N/Fast Transigate Reflectoscope) and the transducer holder is diagrammed in Figure 8.

C. GUN BARREL REFERENCE STANDARD

In order to assure that the design intent had actually been accomplished in the lens and transducer holder, establish a workable test procedure, and provide a basis for calibration prior to and during a gun barrel inspection, a special Gun Barrel Reference Standard was designed and produced, Figures 9 and 10. The depth position of each hole was calculated to locate the top (toward OD) surface of a .060 inch side-drilled-hole (SDH) at even depths between 0.100 inch and 2.500 inch from the bore. Angular positioning assured that no hole would interfere with the adjoining holes by virtue of the ultrasound beam width. They were produced with a twist drill to a length of .75 inch. These holes served to calibrate the time-axis (horizontal on the oscilloscope) only, and not amplitude. The six 0.010" by 1.25" dia. saw-cuts were produced to approximate the shape and size of shallow propagating fatigue cracks. They confirmed the depth calibration of the 0.100 inch detectability threshold and gave a reasonably accurate impression of amplitudes and shape and orientation effects expected from real fatigue cracks of that size. The finished Gun Barrel Reference Standard is pictured in Figure 11.

FIGURE 7

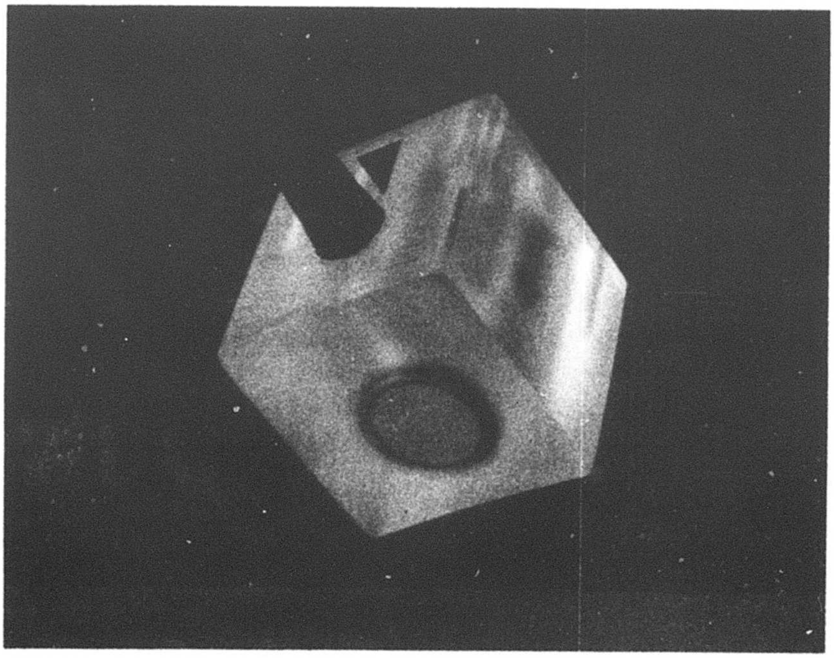
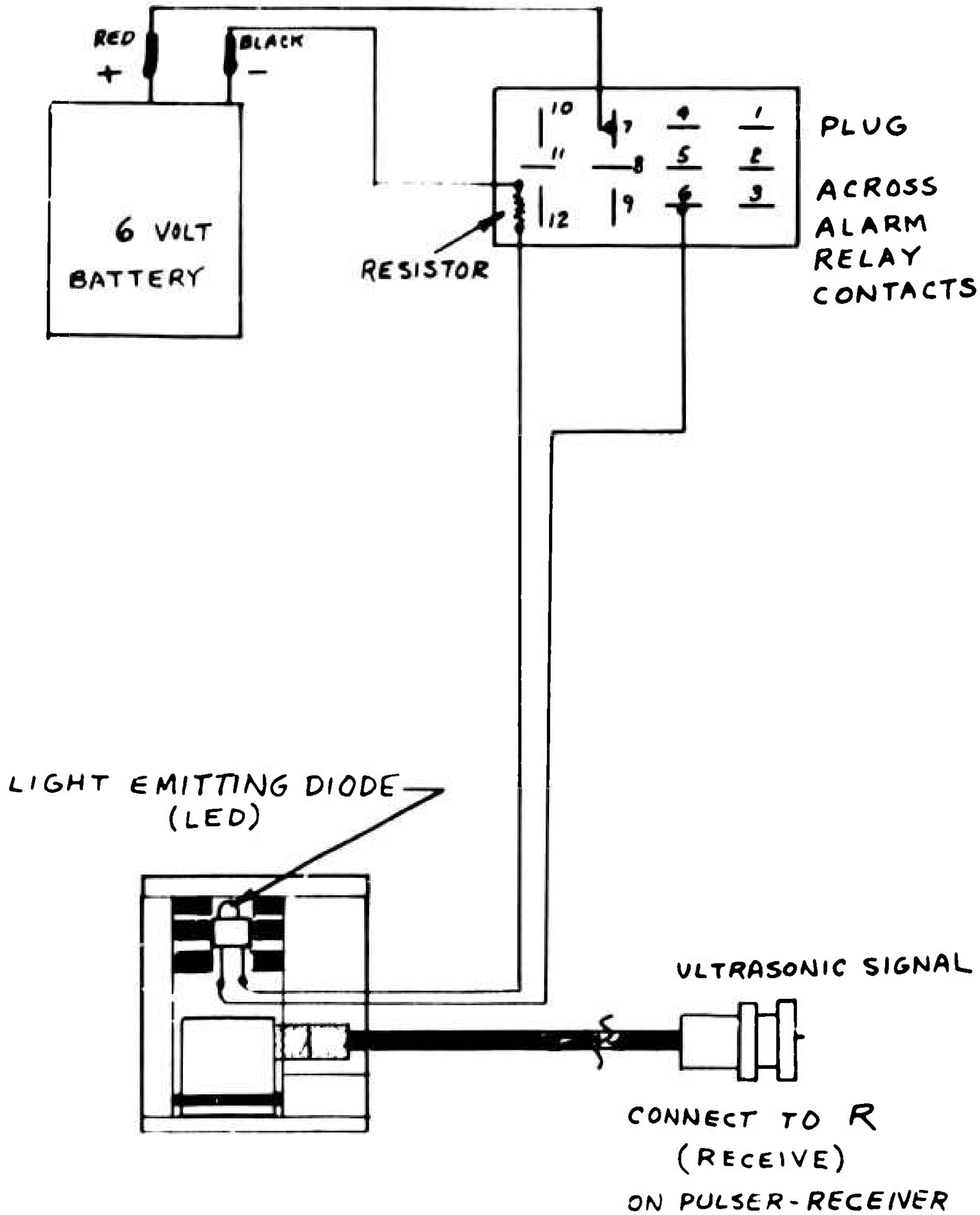


FIGURE 8



RED
+
BLACK
−
6 VOLT
BATTERY
RESISTOR
10
11
12
7
8
9
4
5
6
1
2
3
PLUG
ACROSS
ALARM
RELAY
CONTACTS
LIGHT EMITTING DIODE
(LED)
ULTRASONIC SIGNAL
CONNECT TO R
(RECEIVE)
ON PULSER-RECEIVER

FIGURE 9

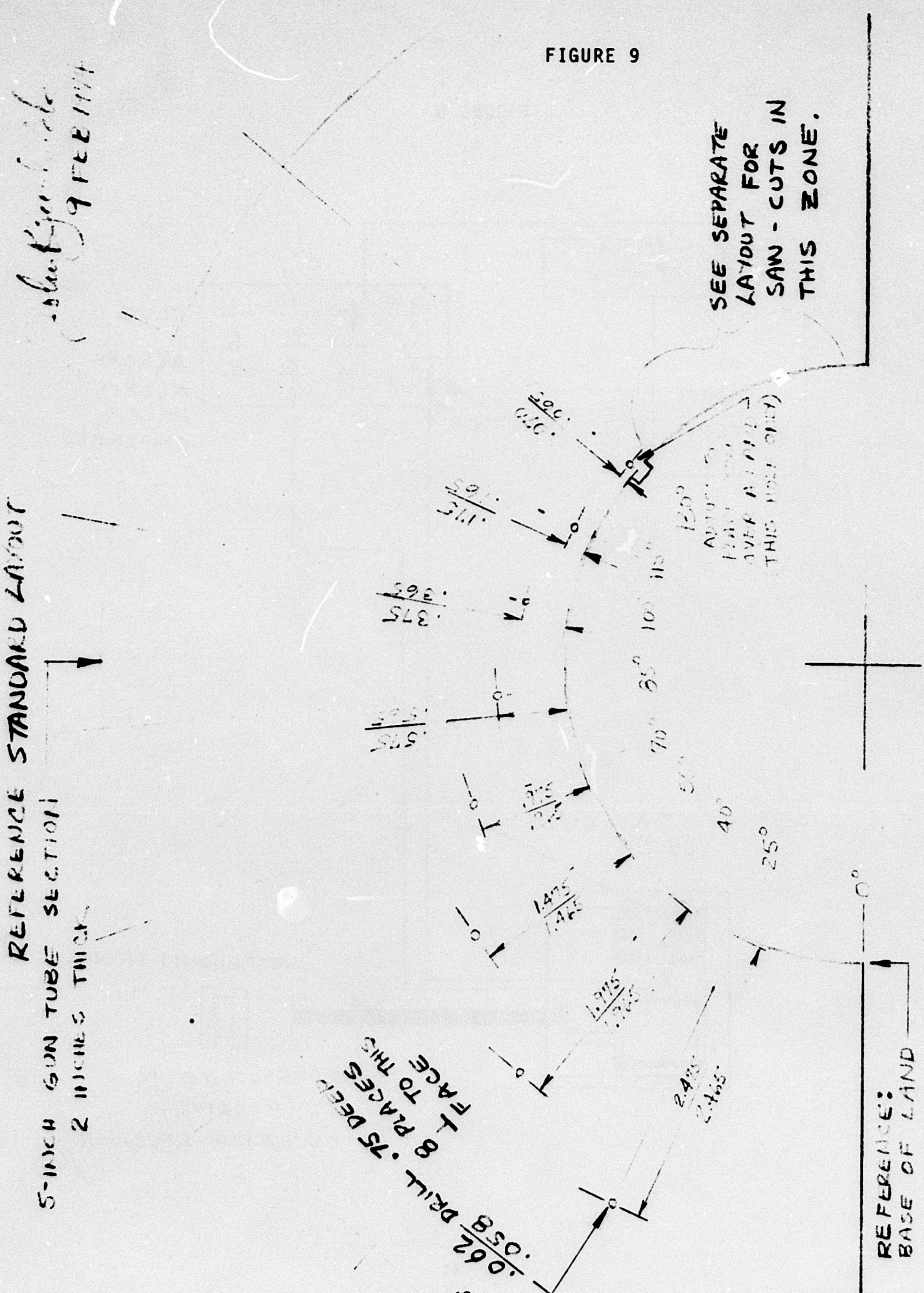

REFERENCE STANDARD LAYOUT
5-INCH GUN TUBE SECTION
2 INCHES THICK
SEE SEPARATE LAYOUT FOR SAW - CUTS IN THIS ZONE.
.062/.058 DRILL .75 DEEP
8 PLACES TO THIS FACE
REFERENCE: BASE OF LAND
2.475/2.465
1.975/1.965
1.475/1.465
.375/.365
.115/.105
0°
25°
40°
70°
85°
100°
115°
130°

FIGURE 10

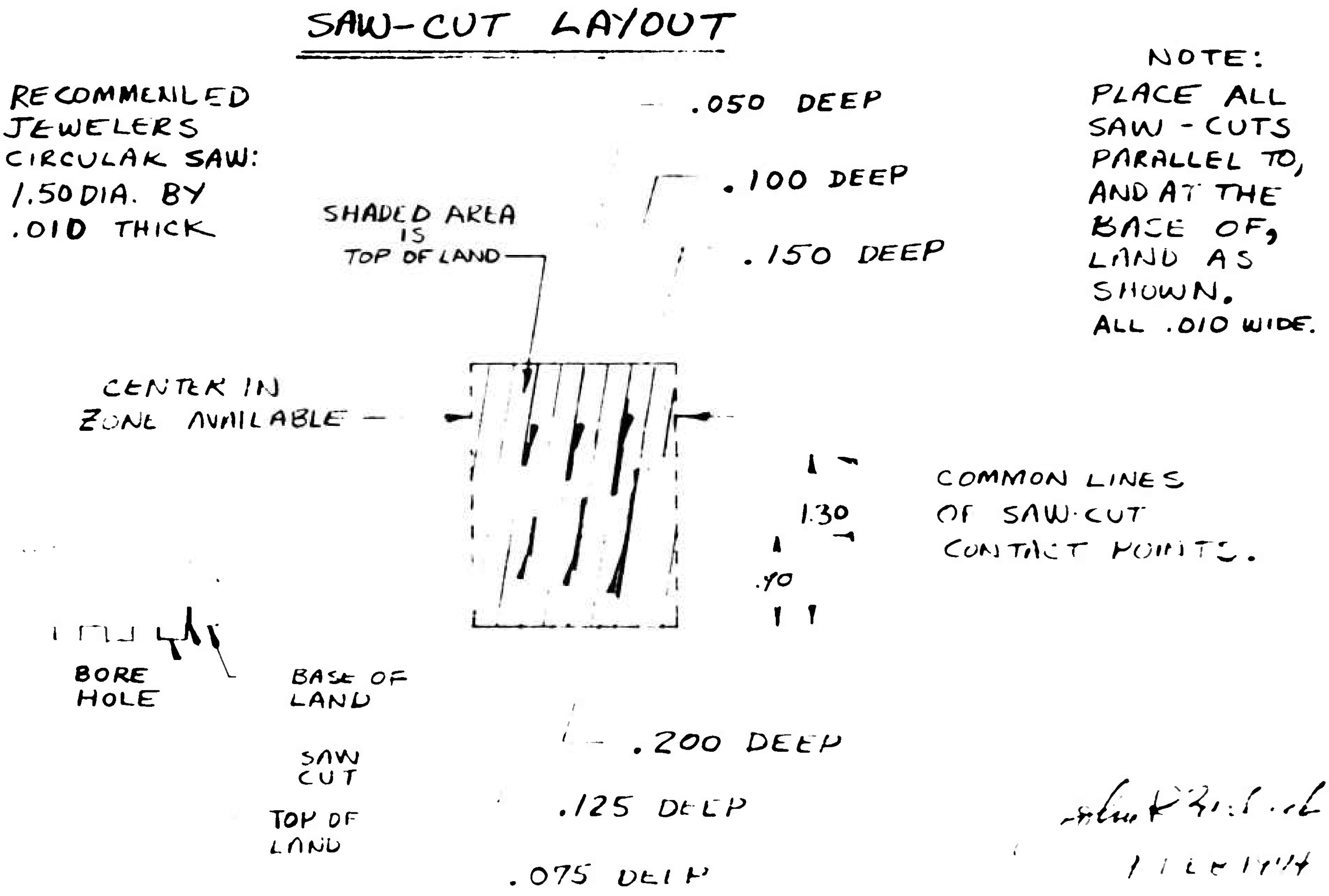
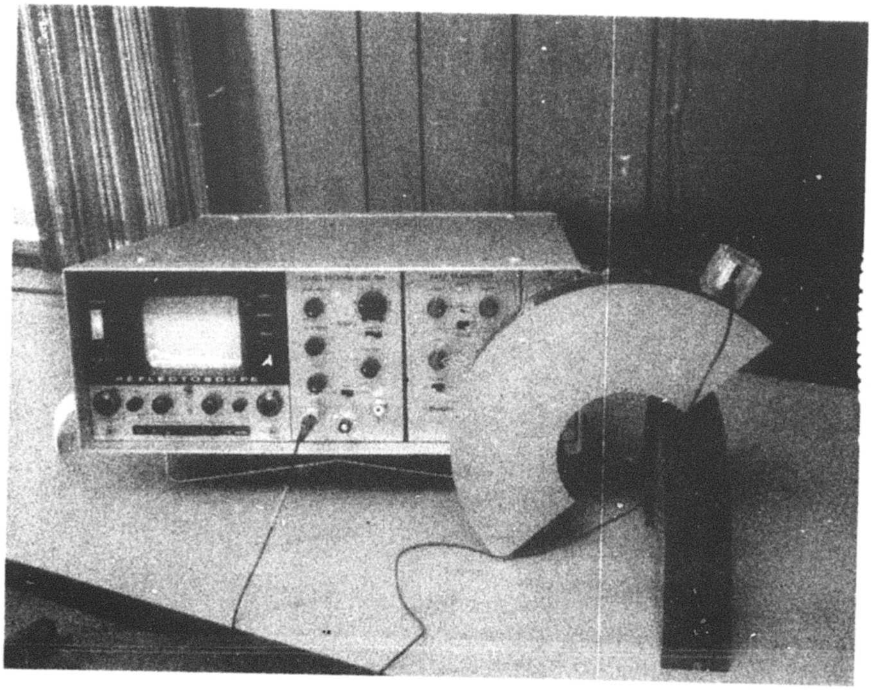

SAW-CUT LAYOUT
RECOMMENDED JEWELERS CIRCULAR SAW: 1.50 DIA. BY .010 THICK
SHADED AREA IS TOP OF LAND
CENTER IN ZONE AVAILABLE
.050 DEEP
.100 DEEP
.150 DEEP
.200 DEEP
.125 DEEP
.075 DEEP
1.30
.90
COMMON LINES OF SAW-CUT CONTACT POINTS.
NOTE: PLACE ALL SAW-CUTS PARALLEL TO, AND AT THE BASE OF, LAND AS SHOWN. ALL .010 WIDE.
BORE HOLE
BASE OF LAND
SAW CUT
TOP OF LAND

FIGURE 11



ULTRASONIC TEST PROCEDURE

A. GENERAL DISCUSSION

The objective of the test procedure was to detect fatigue cracks, measure their size and orientation, and plot their propagation with cyclic loading. The UM771 Reflectoscope was set-up to maximize the time-axis resolution of depth as measured from the bore-echo leading edge leftwise to the leading edge of the crack tip indication. Sensitivity gain and reject settings were adjusted to observe the saw-cut tip indications at maximum amplitude without bringing spurious scattered reflection signals up into the baseline. Sweep delay time adjustment allowed the convenient display of the bore echo at the right side of the oscilloscope, with inspection depth to the left (spread to maximum practical resolution). Because the instrument sweeps from left-to-right, this was an unusual but fully practical set-up. The time-gate data window was set to operate from a convenient point on the left to just before the bore echo, providing a step adjacent to the bore echo wide enough to be easily observed, but less than the minimum crack depth resolution threshold of 0.100 inch. The amplitude gate threshold level was set to the lowest level which would avoid the alarm being triggered by spurious scattered signals. Pulse length was minimized to provide best depth resolution. The exact set-up conditions used throughout the gun barrel test program are given in Table I. Main settings were used for newly propagating crack measurement, while the values in parentheses were used for deep cracks. Graphical plots of the graticule scale versus crack tip depth is presented in Figure 12. The equation of each line is also provided, and used to calculate Table II. Note that each minor division equals 0.017 inch of crack growth for the maximized resolution.

TABLE I

AI UM771/10N/TRANSIGATE SETTINGS

OSCILLOSCOPE/TIMER D.

Div. (Dial) 240 (063)

Material (Dial) 036

Set-Up 100

Pulse Rate 1.0 KHz

In/Div EXP/.02/1 10 (EXP/.5)

Calibrated Sweep

10N PULSER RECEIVER

Pulse Length Minimum, Full CCW

Tune Maximize Back Reflection

Reject 8 O'Clock Enough to Clear Baseline

Sensitivity 1.0 x 10 (1.0 x 1)

Freq. 5.0 MHz

Test Normal

5.0/.50 SFZ Transducer on R Connector (Receive)

FAST TRANSIGATE

Start 3 Leading edge of time window at 1.2 Div. with 2.5 Radius position hole leading edge at 1.5 Div. and peak 2nd reflection at 1.8 Div. (with in/Div. set at EXP/.5 1.2 goes to 5.2. Set the 2.5 hole leading edge at 2.3 Div., 1st reflection. Set the window leading edge at 2.2 Div.)

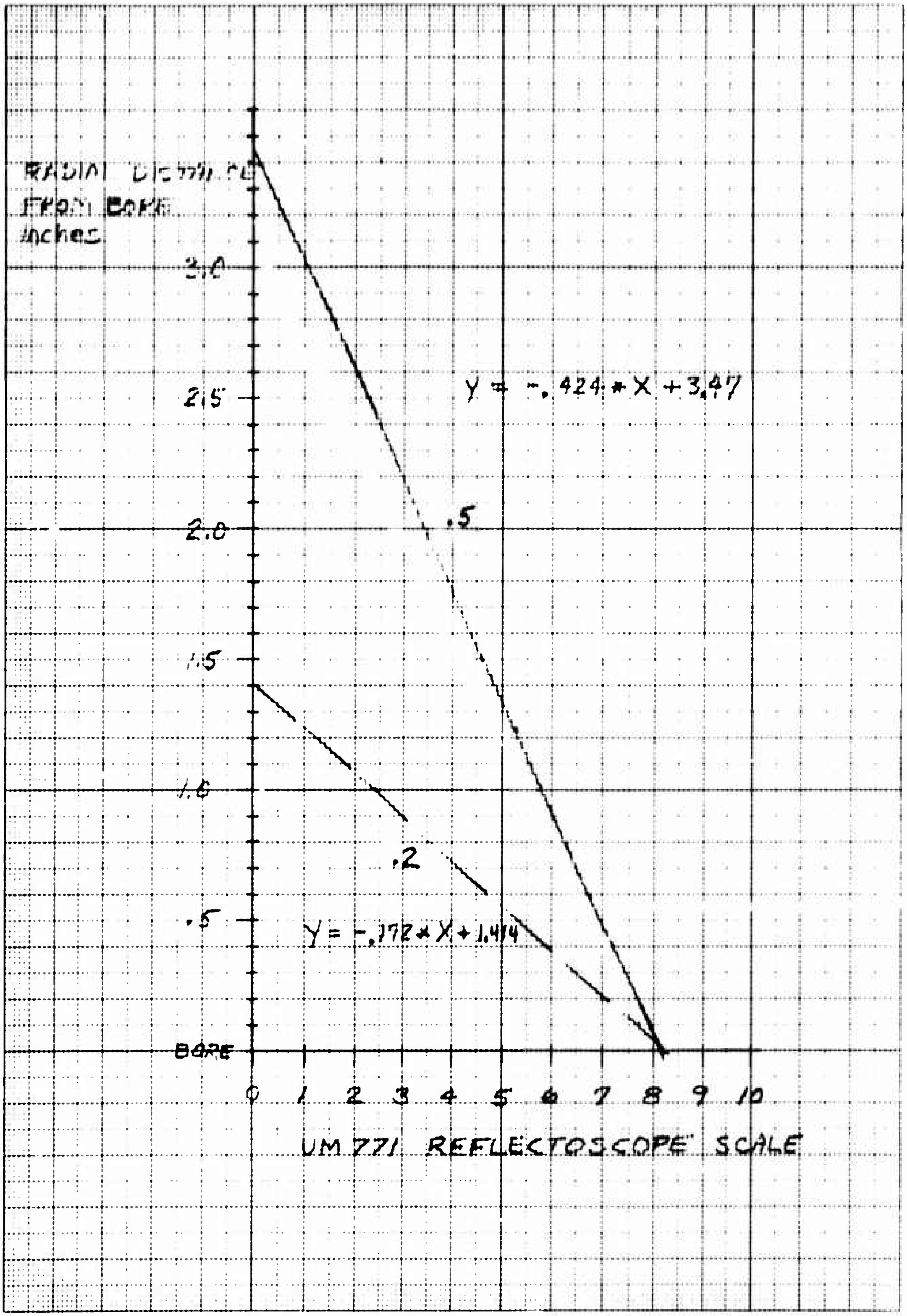
Length 2 (3) Trailing edge of time window at 8.0 Div. with bore reflection at 8.2 Div.

+Auto Reset Level at 15% (20%) Be careful with reject

Gate Baseline At 0% FSA SYNC Main Pulse

½ Hour For Stabilization Watch For Transducer Motion in Shoe

FIGURE 12



J.R. Z[illegible]
1 MAR 74

TABLE II

X1 = 2.3 X2 = 8.2
Y1 = 2.5 Y2 = 0 .5

SLOPE = -.423729 Δ = .042"/DIV
INTERCEPT = 3.47458

RADIAL DISTANCE FROM BORE, INCHES	UM771 TIME SCALE, DIVISIONS
3.47458	0
3.4322	.1
3.38983	.2
3.34746	.3
3.30508	.4
3.26271	.5
3.22034	.6
3.17797	.7
3.13559	.8
3.09322	.9
3.05085	1.
3.00847	1.1
2.9661	1.2
2.92373	1.3
2.88136	1.4
2.83898	1.5
2.79661	1.6
2.75424	1.7
2.71186	1.8
2.66949	1.9
2.62712	2.
2.58475	2.1
2.54237	2.2
2.5	2.3
2.45763	2.4
2.41525	2.5
2.37288	2.6
2.33051	2.7
2.28814	2.8
2.24576	2.9
2.20339	3.
2.16102	3.1
2.11864	3.2
2.07627	3.3
2.0339	3.4
1.99153	3.5

X1 = 2.4 X2 = 8.2 .02×10
Y1 = 1 Y2 = 0

SLOPE = -.172414
INTERCEPT = 1.41379 Δ = .017"/DIV

RADIAL DISTANCE FROM BORE, INCHES	UM771 TIME SCALE, DIVISIONS
1.41379	0
1.39655	.1
1.37931	.2
1.36207	.3
1.34483	.4
1.32759	.5
1.31034	.6
1.2931	.7
1.27586	.8
1.25862	.9
1.24138	1.
1.22414	1.1
1.2069	1.2
1.18966	1.3
1.17241	1.4
1.15517	1.5
1.13793	1.6
1.12069	1.7
1.10345	1.8
1.08621	1.9
1.06897	2.
1.05172	2.1
1.03448	2.2
1.01724	2.3
1.	2.4
.982759	2.5
.965517	2.6
.948276	2.7
.931034	2.8
.913793	2.9
.896552	3.
.87931	3.1
.862069	3.2
.844828	3.3
.827586	3.4
.810345	3.5

TABLE II (Cont'd)

1.94915	3.6	.793103	3.6
1.90678	3.7	.775862	3.7
1.86441	3.8	.758621	3.8
1.82203	3.9	.741379	3.9
1.77966	4.	.724138	4.
1.73729	4.1	.706897	4.1
1.69492	4.2	.689655	4.2
1.65254	4.3	.672414	4.3
1.61017	4.4	.655172	4.4
1.5678	4.5	.637931	4.5
1.52542	4.6	.62069	4.6
1.48305	4.7	.603448	4.7
1.44068	4.8	.586207	4.8
1.39831	4.9	.568966	4.9
1.35593	5.	.551724	5.
1.31356	5.1	.534483	5.1
1.27119	5.2	.517241	5.2
1.22881	5.3	.5	5.3
1.18644	5.4	.482759	5.4
1.14407	5.5	.465517	5.5
1.1017	5.6	.448276	5.6
1.05932	5.7	.431035	5.7
1.01695	5.8	.413793	5.8
.974576	5.9	.396552	5.9
.932203	6.	.37931	6.
.889831	6.1	.362069	6.1
.847458	6.2	.344828	6.2
.805085	6.3	.327586	6.3
.762712	6.4	.310345	6.4
.720339	6.5	.293103	6.5
.677966	6.6	.275862	6.6
.635593	6.7	.258621	6.7
.59322	6.8	.241379	6.8
.550848	6.9	.224138	6.9
.508475	7.	.206897	7.
.466102	7.1	.189655	7.1
.423729	7.2	.172414	7.2
.381356	7.3	.155172	7.3
.338983	7.4	.137931	7.4
.			
.29661	7.5	.12069	7.5
.254237	7.6	.103448	7.6
.211865	7.7	8.62069E-02	7.7
.169492	7.8	6.89656E-02	7.8
.127119	7.9	5.17242E-02	7.9
8.47459E-02	8.	3.44828E-02	8.
.042373	8.1	1.72414E-02	8.1
1.26660E-07	8.2	5.21541E-08	8.2

B. CALIBRATION PROCEDURE

1. Set-up the instrument and allow to stabilize for ½ hour.
2. Adjust the horizontal knob to place the bore echo at 8.2 divisions.
3. Adjust time-gate start to set the marker edge at 1.2 divisions.
4. Adjust time-gate length to set the marker edge at 8.0 divisions. This leaves 0.2 division (2 minor division lines) between the marker edge and the bore echo.
5. Check the 2.5 inch depth calibration hole (second reflection) to assure it rises at 1.5 divisions and peaks at 1.8 divisions, Figure 13a. Amplitude should be approximately 20%.
6. If time position requires adjustment use the Material Dial, keeping the bore echo at 8.2 divisions. Then repeat steps 2 through 5.
7. Check the 0.100 inch depth calibration hole. It should be easily observed with its leading edge at 7.6 divisions. Figure 13b.
8. Check the 0.100 inch depth saw-cut for a leading edge rise at 7.6 divisions. Figure 13c.
9. Check other holes and saw cuts as desired to assure minimum depth threshold and data window span.
10. Set amplitude gate to 20% using the second reflection signal from the 2.5 inch depth hole. Check alarm lights and buzzer.

NOTE: A similar calibration procedure was used for the deep-crack set-up.

NOTE: A water filled gun barrel bore reduces the bore-echo by only 5% FSA from the air-filled gun barrel bore echo. This is as expected and changes no part of the calibration or test procedure. There is no effect on crack-tip echos.

FIGURE 13 a

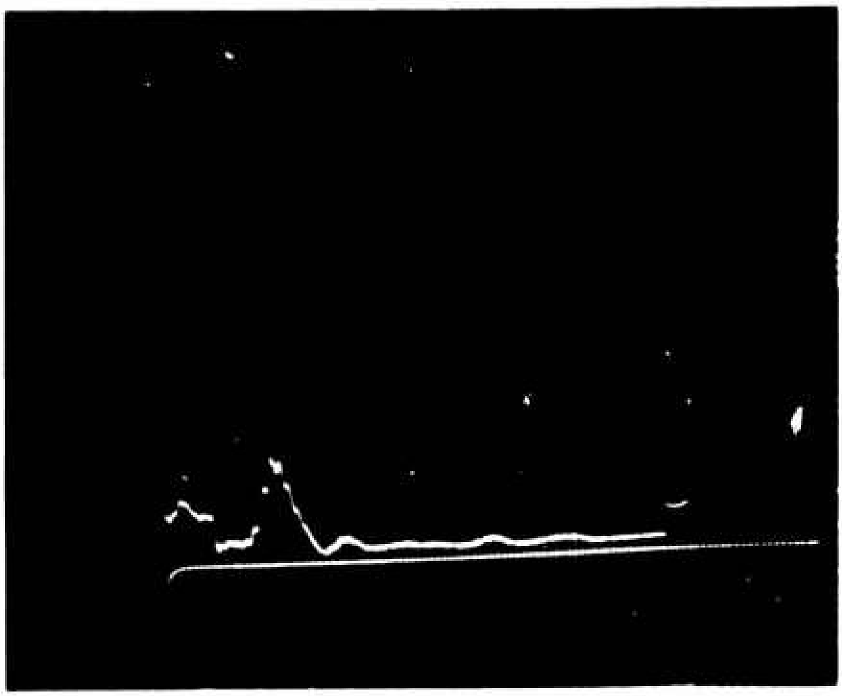


FIGURE 13 b

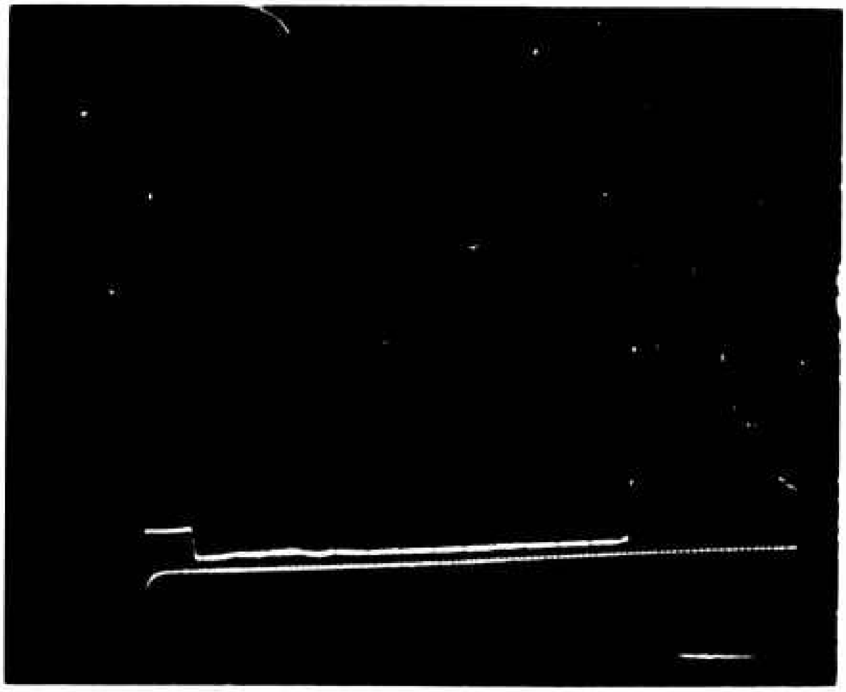
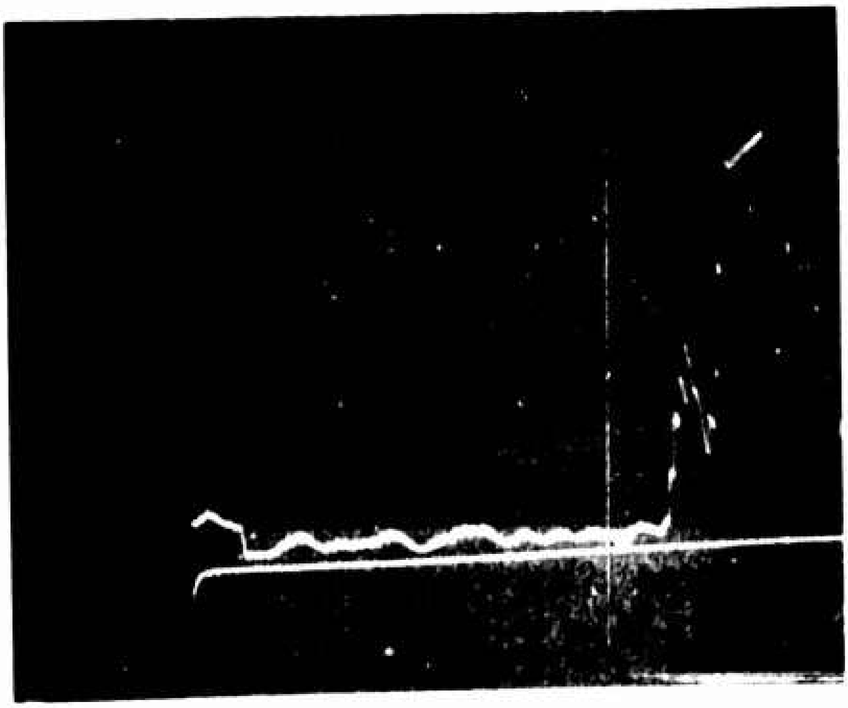


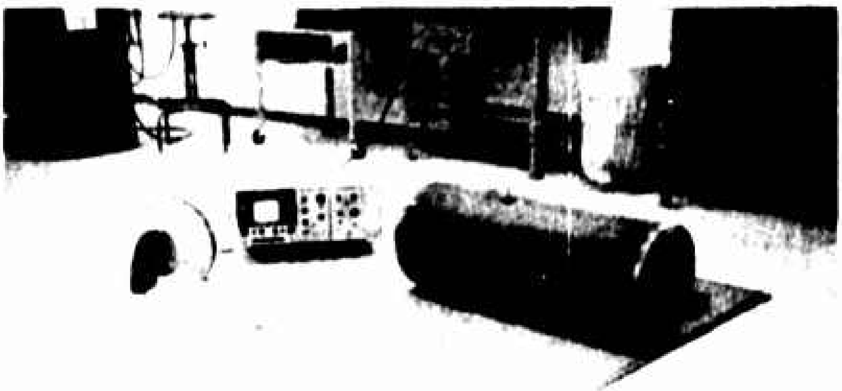
FIGURE 13 c



C. GUN BARREL TEST PROCEDURE

1. Set-up the instrument and allow to stabilize for ½ hour.
2. Perform a thorough calibration.
3. Place the transducer holder on the gun barrel, Figure 14.
4. Check the location of the bore-echo in relation to the graticule scale. Do not adjust from the calibration settings.
5. Scan the gun barrel OD surface in conveniently small sections, using axial scan with circumferential index, or circumferential scan with axial index. Mechanical aids to assure complete coverage are acceptable. Note that the inspection path is less than ½ inch by ½ inch, directly under the ultrasonic transducer.
6. Whenever it is observed that the bore echo has drifted from 8.2 divisions or the time-gate length marker has drifted from 8.0 divisions, recalibrate on the Gun Barrel Reference Standard.
7. Use the alarm buzzer to augment the transducer alarm light whenever practicable.
8. For detection of shallow fatigue cracks it is wisest to observe the indications on the oscilloscope in addition to the alarms.
9. As each significant indication is encountered, enter the OD surface location and graticule scale position on the appropriate form.
10. Mark each significant indication on the gun barrel OD surface using a china marker pencil or equivalent.
11. At the end of all testing recheck the full calibration procedure.

FIGURE 14



GUN BARREL TEST DATA

A. INSPECTION PRIOR TO ELECTROHYDRAULIC IMPULSE CYCLING

A thorough inspection scan was performed over the gun barrel test section OD surface while it lay on the floor at CTL. All indications which exceeded the 20% amplitude gate were recorded, marked on the gun barrel, and reported, Figure 15. Each of these was reinspected using lower time-axis resolution and each was found to correspond to second reflections from near-OD-surface steel grain structure or inclusions/porosity. They did not exhibit crack-echo behavior. The numbers are graticule scale divisions. Note that the indications lie along the extrusion rolling direction of the gun barrel, essentially across the rifling direction, in bands 180 degrees opposite each other.

This data served as a baseline on which to observe crack initiation and growth over the course of acoustic impulse cycling.

B. INSPECTION AFTER 1009 CYCLES

A thorough inspection scan was performed over the gun barrel in its test-rig mounting at Sonoform, Inc., San Diego, California. The bore was empty of water. All of the original indications were reconfirmed and no changes or new indications were observed, Figure 16.

C INSPECTION AFTER 1600 CYCLES

A thorough inspection scan was performed over the gun barrel in the test-rig mounting at Sonoform, Inc. The bore was filled with water. Five indications adjacent to, or riding on, the bore echo were observed, indicating the initiation and growth of cracks to much less than .100 inch depth, Figure 17.

D. INSPECTION AFTER 4751 CYCLES

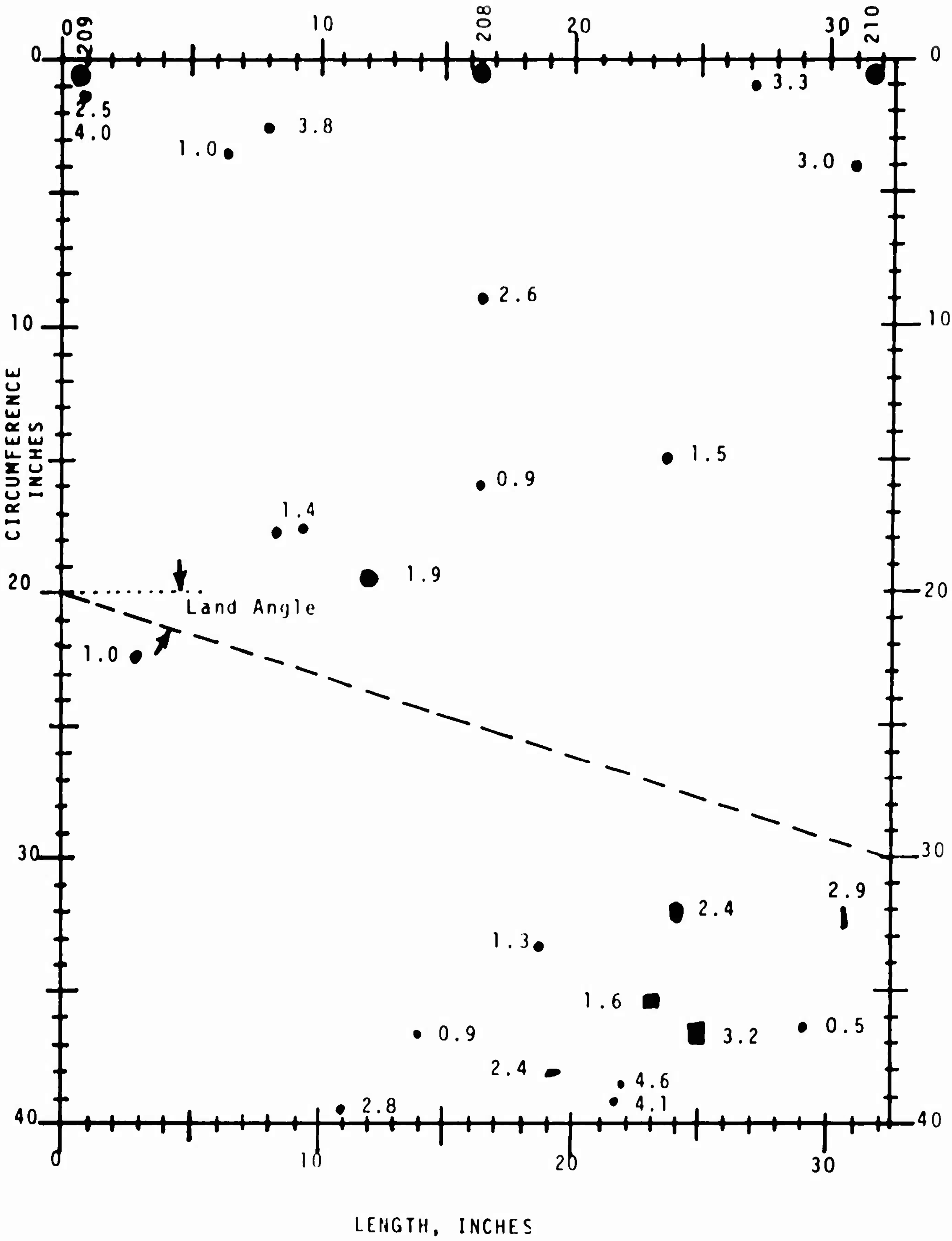
A thorough inspection scan was performed over the gun barrel on the floor at the NOSL Manufacturing Technology Facility. For this test the sensitivity gain was increased to 2.0 x 10. and the gate held at 20%. This essentially doubled the inspection capability without excessive interference from spurious scattered signals.

Three out of five indications from the previous inspection were reconfirmed and found to behave as crack-tip echos. Their persistance and peaks ranged between 7.0 and 7.5 respectively on the graticule scale, indicating crack depths ranging from .121 to .206 inches. Four new such indications were observed, marked on the gun barrel and reported, Figure 18.

As an added assurance, a bare 5 MHz transducer was used to obtain pulse-echo signals from the opposite end of the 3-foot long gun barrel section. A clean back-echo was observed and reflections off the pressure transducer holes were also indicated. No reflections indicative of large fatigue cracks were observed.

FIGURE 15

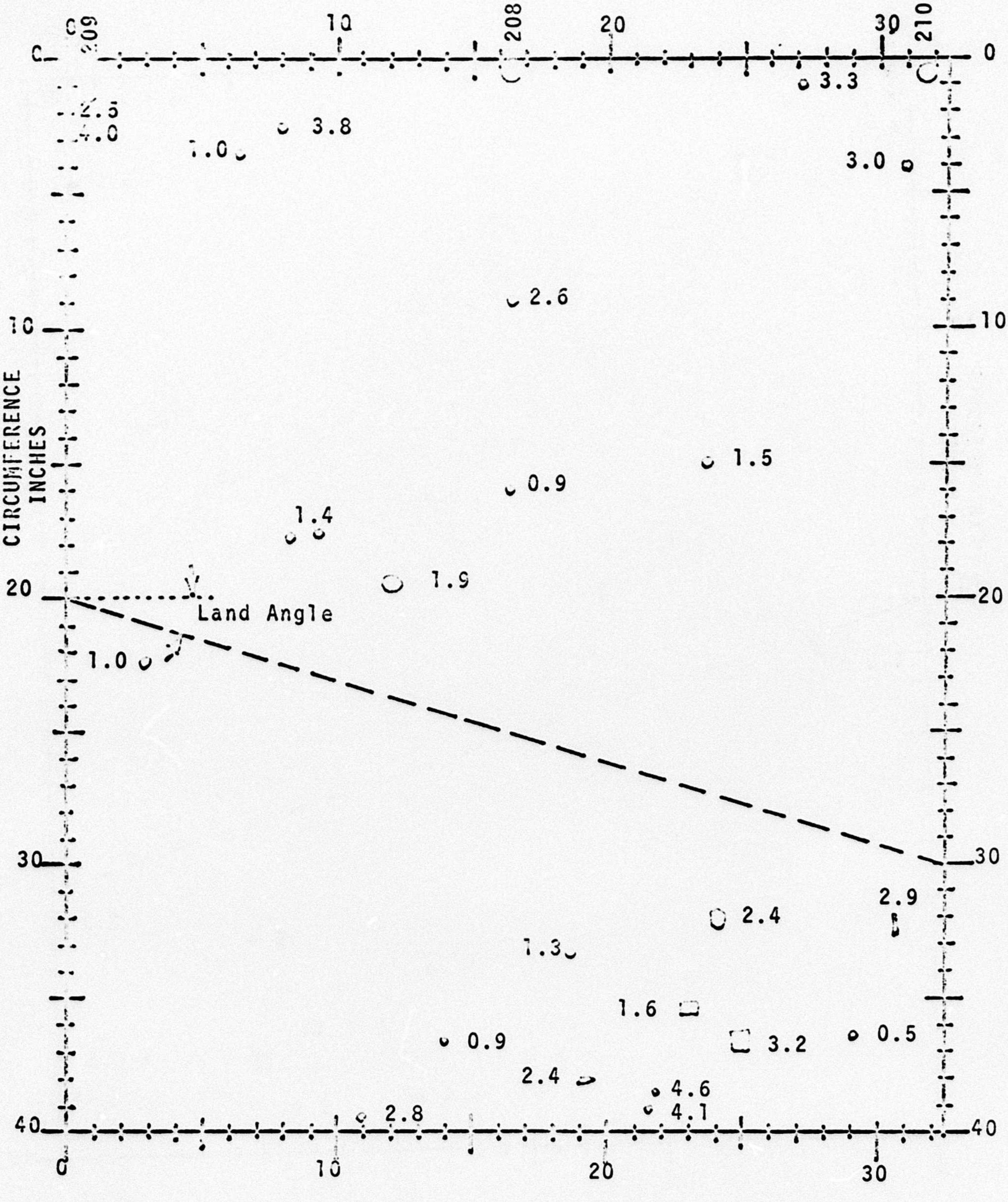
INSPECTION PRIOR TO ELECTROHYDRAULIC IMPULSE CYCLING



Numbers are divisions
at .02 x 10 time scale

FIGURE 16

INSPECTION AFTER 1009 CYCLES

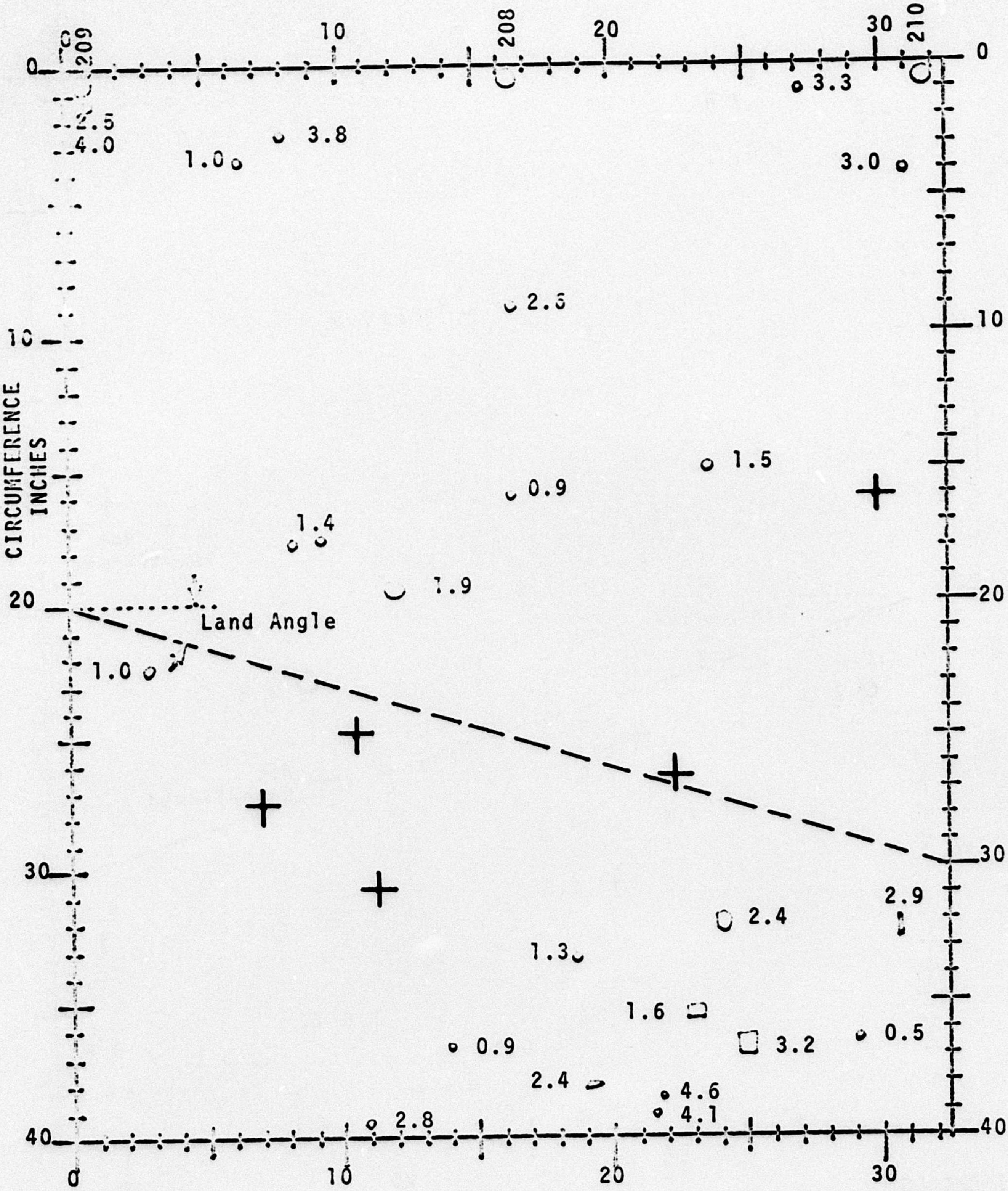


1009 CYCLES
NO CHANGE

Numbers are divisions
at .02 x 10 time scale

FIGURE 17

INSPECTION AFTER 1600 CYCLES

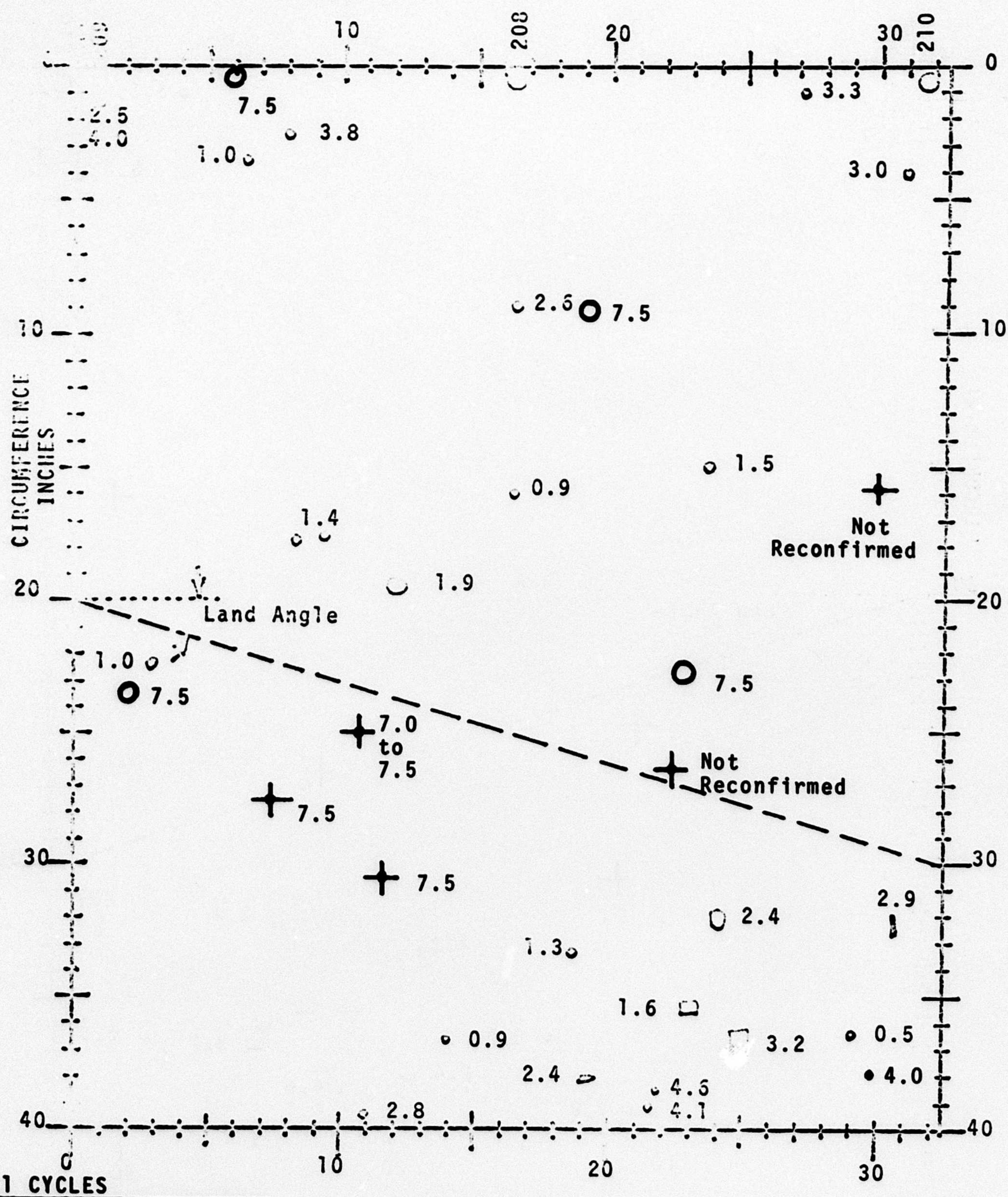


1600 CYCLES
5 NEW INDICATIONS

Numbers are divisions at .02 x 10 time scale

FIGURE 18

INSPECTION AFTER 4751 CYCLES



4751 CYCLES
3 RECONFIRMED & GROWING
4 NEW INDICATIONS

Numbers are divisions at .02 x 10 time scale

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. The hand-scanning contact ultrasonic technique developed was adequate to detect fatigue cracks in the 5-inch breach-end gun barrel section.

2. Time-axis resolution was improved from The Army experience of .100 inch per minor division to .017 inch per minor division.

3. Amplitudes of echoes from the bore and calibration holes were found to be significantly greater than for the bare transducer although no detailed substantiation was performed. This was attributed to the focused lens design.

4. Indications related to shallow fatigue cracks were observed.

B. RECOMMENDATIONS

1. Further evaluate the developed technique to measure its capability to detect real fatigue cracks over a wide range of crack depths from bore.

2. Establish a task to procure transducer lens design calculations which cover all applications to shipboard and storage gun barrel dimensions.

3. Investigate gun barrel manufacture quality control automatic inspection systems based on focusing lens immersion or contact techniques.

4. Investigate portable shipboard inspection systems based on focused contact transducers.

REFERENCES

1. James E. Miller
   Ultrasonic Measurement of Crack Depth in Thick-walled Cylinders
   Technical Report INVT-7017
   Benet R & E Laboratories
   Watervliet Arsenal, Watervliet, New York 12189

   "Cleared for public release, distribution unlimited"

   Referenced in Report Text and Appendix I